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Crew Fatigue and Performance on U.S. Coast Guard Cutters

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16. Abstract (MAXIMUM 200 WORDS)

This report describes an analysis of crew workload and fatigue on Coast Guard cutters. Descriptive measures were obtained on five cutters of three types under normal operations. Evidence of mild fatigue, specifically daytime sleepiness and a degradation of vigilance performance, was observed in many crew members. This study documented levels of workload, performance, and fatigue found in normal, daily Coast Guard cutter operations. Principles of industrial chronohygiene were considered in light of the analysis of crew member sleep patterns, circadian rhythms, and watch schedules. This analysis led to recommendations for watch schedule alternatives that may reduce the probability of crew daytime sleepiness and vigilance performance degradation.

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EXECUTIVE SUMMARY

THE PROBLEM

The Coast Guard (CG) faces continuing reductions in operating budgets and personnel, while it is expected to maintain current levels of service and performance across a broad range of missions. A recent CG report developed streamlined alternatives to current crewing practices without changing the core characteristics, capabilities, or attributes of CG cutters (U.S. Coast Guard, 1996). Potential crew reductions pose challenges for mission effectiveness, crew training and qualifications, onboard maintenance, and logistics. Reductions in crew complement pose questions of risk in the areas of crew workload, fatigue, and, ultimately, safety and mission effectiveness. Data were needed as a benchmark for levels of crew fatigue to enable informed judgments to be made about the tradeoffs between cost reduction and risks associated with crew reduction.

THE APPROACH

This report presents the results of a descriptive effort to determine whether present operations aboard USCG cutters may contribute to excessive crew fatigue, thus exposing crew members to unnecessarily high risks of incidents, accidents, injury, and mission failure. The approach included assessments of workload (stress), effort (strain), performance, and fatigue of selected crew members on selected cutters during operational patrols.

BACKGROUND

Many books have been written about the abstract concept, fatigue. In field studies such as this, fatigue is usually defined "operationally" in terms of performance decrements. As discussed in the report, performance decrements are not a fully satisfactory definition of fatigue because performance may not change in a predictable manner in fatigued individuals. For this project, fatigue was viewed as a *covert* result of the costs generated by effort and performance which, in turn, were responses to work demands. Evidence of fatigue was sought in the perceptions of the crew members, in levels of task performance that were diminished below reasonable expectations, and in behaviors associated with sleepiness[1]. We divided fatigue into three categories: acute fatigue, cumulative fatigue and circadian rhythm[2] effects. Acute fatigue is limited to the effects of a single duty period, such as a 9 to 5 work day. Cumulative fatigue occurs when there is inadequate recovery between these duty periods. Thus, cumulative fatigue usually presents a picture of day-to-day changes for the worse.

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[1] Fatigue is more rigorously defined by physiological measures, such as electroencephalography (brain waves) or assays of certain hormones in body fluids. Since it was not feasible to do these kinds of tests on board, we used indirect evidence of fatigue.

[2] sir-kay'dee-an: an oscillation with a period of about one day, 24 h. The daily, 1° C swing in body temperature, with a low before dawn and a peak in the evening, is the most familiar circadian rhythm. However, many hormones and many kinds of performance, physical and mental, also have normal rhythms with the same or different phase relationships to the day-night cycle.

The operational impact of a human circadian rhythm that is not aligned with the day-night cycle is familiar to anyone who has suffered jet lag. One may experience sleepiness, sleeplessness, an inability to sustain attention, perceptions of physical fatigue, and a general malaise. Research on shift workers has shown that work-schedule irregularity commonly contributes to sleep disruption, performance degradation, and circadian rhythm disruption. These factors were assessed in the present study. Ship motion associated with high sea states was also studied for its contribution to sleep disruption and increased physical effort during waking activities.

METHODS

Baseline data on issues related to crew fatigue were collected during portions of six patrols on three types of Coast Guard cutters. There were no pre-determined manipulations of work conditions aboard the cutters. This was an empirical, observational study, without intervention. The investigation focused primarily on three Reliance class (210') medium endurance cutters (WMECs). The baseline analyses on the three WMECs were supplemented by the analysis of one cutter in each of two additional vessel classes, the Bay class (140') ice-breaking tug (WTGB) and the Hamilton class (378') high endurance cutter (WHEC).

Crew member selection for this project was generally initiated by the Executive Officer, assisted by Department Heads, and approved by the Commanding Officer. A typical sample on a cutter was about 20 crew members composed of about 2/3 watchstanders and 1/3 non-watchstanders, and including several officers.

The workload demanded of a crew member was viewed as a stress, to which the crew member would respond with some evidence of strain, or effort. A Crew Member's Daily Log provided information about the crew members' daily cycles of work, rest, and sleep, as well as other information. Metabolic task descriptions allowed rough estimates of the metabolic demand placed upon the crew member by the job. Ship motion was described in terms of swell and wind/wave height and perceptions of the research personnel. Crew members provided ratings of perceived mental and physical workload, motion discomfort, and motivation.

Crew member performance was measured indirectly by presenting and collecting data from computerized tests. The tests required competence in (1) visual search mechanisms, encoding, decoding, and rote recall; (2) visual pattern recognition and spatial memory, related to crew members' abilities to use a pattern-matching approach to system failure diagnosis; (3) vigilance, the ability to remain alert and watchful in a boring environment; (4) visual temporal acuity, the ability to resolve rapid changes in a visual pattern; and (5) fine motor control and speed. The testing systems were located together at one (WTGB) or two (WHEC, WMEC) testing stations on each cutter. The crew members were asked to test at least twice per day.

Circadian rhythm alignment (with the day-night cycle) of body temperature was assessed by self-measurement. Circadian rhythm problems were characterized by a flattening or phase shift in this rhythm. Acute fatigue was measured as pre-post-work and -watch and -sleep changes in perceptions of sleepiness. Evidence for cumulative fatigue was sought by examining changes in sleepiness and performance across days of data collection.

MAIN FINDINGS, CONCLUSIONS, AND RECOMMENDATIONS

Approximately 10 to 45% of the crew members displayed one or more signs of mild fatigue. A greater proportion of the crew would be expected to suffer from fatigue, and the associated safety risks and decreased mission capability, under conditions such as high tempo operations, significant maintenance requirements, reduced crew levels, and/or sustained high sea states.

Watchstanders averaged about 9.7 hours of work per day while non-watchstanders averaged about 8.3 hours per day, across all patrol days. Industrial investigations have shown that errors tend to increase disproportionately after about 8 hours of work in one day (cf. Miller, 1992). Overall, the work schedule caused many crew members to work 1.4 to 1.75 times as many hours as they would, for example, in a classic 40-hour week.

Generally, the crew members acquired adequate sleep with respect to their self-reported ideal amounts, but the quality of that sleep was questionable for two reasons. First, the crew members tended to split their sleep into more than one period per day. Watchstanders split their sleep more than non-watchstanders and received less sleep. Splitting sleep is known to reduce sleep quality (cf. Mitler et al., 1997). Second, the average vigilance performance of crew members was impaired, suggesting a level of fatigue similar to that of laboratory subjects sleeping only five hours per night for a week.

In terms of overall performance on the computer-based performance tasks, the crew members performed well except in the area of vigilance. Generally, vigilance tests are the most sensitive of computerized tests with respect to the detection of sleepiness and fatigue due to sleep disruption (cf. Mackie, 1977). The impaired vigilance performance of the crew members was of concern. Vigilance is the ability to sustain and focus attention in a boring situation, with the goal of quickly and accurately detecting the occurrence of a rare, unpredictable, important event. Obviously, this capability applies to underway tasks such as the monitoring of radar, radio, engine and other systems and visual scanning by topside lookouts. Delayed or inaccurate detections in these areas can be problematic for cutter operations.

There was other evidence of crew member fatigue. First, their overall, average rating of sleepiness was much closer to the description, “Losing interest in remaining awake” than to the description “wide awake.” Second, the circadian rhythm of body temperature was somewhat suppressed in watchstanders. Third, the crew members reported about the same acute changes in sleepiness across single work and watch periods as office workers. Of course, the watch periods were only half as long as office work days, and the crew members worked more hours per day than office workers. Finally, vigilance performance, pattern matching performance and temporal visual acuity all declined from day to day, though the crew members reported no perceptions of accumulating fatigue. This lack of perception of declining abilities mirrors a similar effect of alcohol.

Among all of these observations, the effect of greatest concern for cutter operations is the somewhat degraded vigilance performance of the crew members. Likely causes for this impairment were:

- average number of hours worked per day
- average number of hours of sleep per day
- average number of sleep periods per day
- circadian rhythm suppression
- daily changes in temporal visual acuity
- age (youth)

The interrelationships among these measures and the vigilance measures were examined and the following findings emerged:

Age had a stronger association with crew member vigilance performance than any other factor we examined. Interestingly, greater age was associated with better vigilance performance. This may reflect a somewhat higher level of discipline for paying attention in the older crew members. The total age range of the crew members tested was from 22 to 40 years.

The number of hours of sleep acquired each day was second only to age in its association with vigilance performance. As expected, more sleep was associated with better vigilance performance, greater lapse response speed, and fewer lapses. The total number of hours of work and watch each day was ranked third in its association with vigilance performance. As expected, more work was associated with poorer vigilance performance.

These results suggest that crew members should be given education and training about the impact of reduced sleep on their vigilance performance so that they will realize the need to manage their sleep times and to obtain recovery sleep when needed. In addition, the formal creation of non-traditional periods (such as afternoon naps) for recovery sleep is recommended.

Watchstanders slept less, and split their sleep more, than non-watchstanders. It was clear that the standing of watches had some degree of influence upon the amount of sleep acquired and the number of periods needed to obtain that sleep. As a result of this association, we explored some possibilities for improved watch scheduling. The recommendations were based upon known principles of chronohygiene (Hildebrandt, 1976), namely, giving 24 h of recovery between night work periods and keeping the human circadian rhythm aligned with the day-night cycle. The use of watch rotations that comply with the principles of chronohygiene, would ease the stress and strain experienced by watchstanders.

Crews also should consider an alternative to the observed practice of using late sleeping for night watchstanders and encouraging late sleeping on Sundays by not piping reveille. A constant waking time from day to day is a very strong time cue that helps align the body's rhythm to the day-night cycle. Synchronization (alignment) of the body's rhythm to the day-night cycle helps prevent the general feeling of malaise and other jet-lag-like symptoms, including an increased risk of errors.

It would also be appropriate for crews to establish a mid-afternoon *siesta* period for night workers and to encourage the *siesta* on holidays instead of late sleeping. The *siesta* would be in accordance with the daily biological pattern of human sleepiness and error probability (Mitler and Miller, 1996; Folkard, 1995).

Even though our data were collected during relatively low tempo operations, these crews exhibited signs of fatigue, including reduced levels of vigilance. High tempo operations would be expected to exacerbate these problems, since work-rest schedules would likely be altered, and total sleep achieved would probably be reduced. In order for Coast Guard crews to be *Semper Paratus*, it is recommended that additional studies be undertaken to develop and implement a crew endurance management program for the Coast Guard (see, for example, Comperatore, 1997). Such a program would take a broader look at cutter activities and consider not only individual work-rest schedules, but also drill and training schedules, and sleeping accommodations to determine what types of changes might be made that would improve crew member sleep duration and quality without sacrificing mission requirements. The crew endurance management program would also include training for the crew and commanding officers in order to make crew alertness or “readiness” a part of Coast Guard culture.

This study established baseline levels of workload, performance, and fatigue found in normal, daily Coast Guard cutter operations. Mild fatigue was found in 10-45% of the crew members tested, despite the fact that no high tempo operations were observed. The baseline measures were quantified and are presented as means and standard deviations in appendices to this report. There were recommendations for changes in watch scheduling and for the structures of subsequent studies, but the data from this study cannot be used to make or support any recommendations about the tradeoffs between cost reduction and risks associated with crew reduction.

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LIST OF ACRONYMS

ACRONYM	DEFINITION
AlPat	Alaskan Patrol
AMIO	Alien Migration Interdiction Operations
APTS	Automated Portable Test System
BMC	Chief Boatswain's Mate
CO	Commanding Officer
DAT	Data Acquisition Team
EEG	Electroencephalogram
ESS	Epworth Sleepiness Scale
ETIB	End Time In Bed
FIT	Oculomotor Tester
LE	Law Enforcement
MDI	Motion Discomfort Index
NATO	North Atlantic Treaty Organization
NOAA	National Oceanographic and Atmospheric Administration
PIN	Personal Identification Number
POMS	Profile Of Mood States
PVT	Psychomotor Vigilance Task
SAR	Search and Rescue
SSS	Stanford Sleepiness Scale
STIB	Start Time In Bed
SVASS	Scripps Visual Analog Sleepiness Scale
USCG	United States Coast Guard
WBGT	Wet-Bulb Globe Temperature
WHEC	High Endurance Cutter
WMEC	Medium Endurance Cutter
WOC	Washington- Oregon Coast
WTGB	Ice-Breaking Tug
XO	Executive Officer

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1.0 INTRODUCTION AND PURPOSE

The Coast Guard (CG) faces continuing reductions in operating budgets and personnel, while it is expected to maintain current levels of service and performance across a broad range of missions. A recent CG report developed streamlined alternatives to current crewing practices without changing the core characteristics, capabilities, or attributes of CG cutters (U.S. Coast Guard, 1996). Potential crew reductions pose challenges for mission effectiveness, crew training and qualifications, onboard maintenance, and logistics. Reductions in crew complement pose questions of risk in the areas of crew workload, fatigue, and, ultimately, safety and mission effectiveness. Data were needed as a benchmark for levels of crew fatigue to enable informed judgments to be made about the tradeoffs between cost reduction and risks associated with crew reduction.

The problem of crew fatigue was addressed in the present project. This report describes the results of an empirical effort to determine whether current operations aboard USCG cutters may contribute to excessive crew fatigue, thus exposing crew members to unnecessarily high risks of incidents, accidents, injury, and mission failure. The approach included assessments of workload (stress), effort (strain), performance, and daytime sleepiness of selected crew members on selected cutters during operational patrols. The body of the report is brief, emphasizing only the most important findings of the project. Detailed methods and results can be found in the appendices to the report.

2.0 BACKGROUND

Many books have been written about the abstract concept, fatigue. In field studies such as this, fatigue is usually defined "operationally" in terms of performance decrements, although this is not a fully satisfactory definition of fatigue because performance may not change in a predictable manner in fatigued individuals. For this project, fatigue was viewed as a *covert* result of the costs generated by effort and performance which, in turn, were responses to work demands. Evidence of fatigue was sought in the perceptions of the crew members, in levels of task performance that were diminished below reasonable expectations, and in behaviors associated with sleepiness[3]. We divided fatigue into three categories: acute fatigue, cumulative fatigue and circadian rhythm[4] effects. Acute fatigue is limited to the effects of a single duty period, such as a 9 to 5 work day. Cumulative fatigue occurs when there is inadequate recovery between these duty periods. Thus, cumulative fatigue usually presents a picture of day-to-day changes for the worse.

Anyone who has suffered jet lag is familiar with the operational impact of a human circadian rhythm that is not aligned with the day-night cycle. Consider the inability of an individual from

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the west coast of the United States to awaken refreshed on the first morning of a sojourn on the east coast. At 06:00 on the east coast, this person's brain is operating as if it were 03:00: it is generating sleep activity, reaction times are slowed, aerobic physical capacity is slightly impaired, and the expected frequency of job errors is many times the expected frequency at noon. The person suffers a general perception of malaise. The individual from the U.S. visiting Europe will have similar problems. We suffer the general malaise associated with jet lag until the body's circadian rhythms re-align with the day-night cycle. Similarly, persons who work irregular schedules experience malaise. This is especially true of long-haul truck drivers, who seldom have work schedules that align with the day-night cycle (Mackie & Miller, 1978; Miller 1993; Wylie, Schultz, Miller, Mitler & Mackie, 1996).

Thus, in the present investigation, the circadian rhythm disruption caused by work-schedule irregularity was expected to play an important role in creating fatigue in watchstanders. Sleep disruption (short length, poor quality) caused by work-schedule irregularity, also was expected to play a major role in fatigue development, as described by Colquhoun (1995) and by others (Mitler, Carskadon, Czeisler, Dement, Dinges, & Graeber, 1988; Mitler, Miller, Lipsitz, Walsh, & Wylie, 1997).

Non-watchstanders who worked days and slept nights also were considered to be at risk of experiencing fatigue if ship motion in higher sea states led to sleep disruption. Ship motion was also expected to contribute to physical fatigue during waking activities.

2.1 Previous Investigations of Fatigue While Underway

Human fatigue in at-sea work environments has been studied to only a limited degree. Sanquist and colleagues provided a brief review (Sanquist, Raby, Maloney, & Carvalhais, 1996). They noted the finding of Rutenfranz and colleagues that watchstanders' average sleep lengths were shorter than those of day workers (Rutenfranz, Plett, Knuth, Condon, DeVol, Fletcher, Eickhoff, Schmidt, Donis, & Colquhoun, 1988). They also noted the finding by Rutenfranz et al. that underway sleep quality was better at night than during the day, and that this finding was consistent with previous sleep studies of shift workers. Sanquist and colleagues also noted the conclusion by Colquhoun (1995) concerning the sleep of maritime watchstanders:

> "the typical maritime watchstanding schedule leads to incomplete adaptation of physiological circadian rhythms, and that '*the key to such rhythm adaptation lies in the taking of a single, uninterrupted sleep at the same time of day, each day.*'" (Sanquist et al., 1996, pg. 8, emphasis added by Sanquist et al.)

Sanquist and colleagues investigated crew fatigue in civilian maritime tankers and freighters using self-reporting by 141 crew members across eight ships (Sanquist et al., 1996). They noted daily sleep times that were too short, very short sleep onset times (indicating excessive sleepiness), and "critically low" alertness levels. They reported, among others, these key findings with respect to civilian maritime crew:

- "Critical levels of fatigue occur between 8 and 21 percent of the time, driven primarily by personnel on the 4-on, 8-off schedule…
- "Mariners sleep an average of 6.6 hours per 24-hour period while on shipboard duty -- this is 1.3 hours less than average sleep duration at home. Sleep debt is known to be cumulative and to reduce performance.
- "Watchstanders generally obtain less total sleep (6.6 hours) than other personnel, and the sleep is of lower quality due to fragmentation and physiologically inappropriate sleep times.
- "Port activities significantly alter the timing of sleep. Frequent changes in sleep timing are known to reduce alertness and performance.
- "The nature and distribution of these findings indicate that the work schedule of the watchstanders is the primary contributor to the fatigue problem." (Sanquist et al., 1996, pg. viii)

In a recent study relating fatigue to marine casualties, McCallum, Raby and Rothblum (1996) developed procedures to help Coast Guard Investigating Officers determine whether crew fatigue was a contributing factor. They reported that 33% of personnel injuries and 16% of critical vessel casualties had crew fatigue as a causal or contributing factor. The message from the combination of the Sanquist et al. and the McCallum et al. studies is that crew fatigue plays an important role in marine casualties and that steps can be taken to reduce fatigue by improving crew work-rest cycles.

2.2 Watch Schedules

For industrial shift work scheduling, the word "crew" is used to represent a team assigned to one shift period (Miller, 1992). However, for this discussion, the full complement of ship's personnel is called the crew, made up in part by teams that stand various watches. In many civilian maritime operations, an individual may be assigned permanently to a watch team, for example, the team that stands the 04:00 to 08:00 watch. Thus, the same team is usually on watch, operating the ship, during a given watch rotation each day, for example 04:00 to 08:00 and 16:00 to 20:00. However, on the cutters observed in this study, team membership was not standard. Watchstanders in one Division might stand one 4-h watch each 12 h (1 in 3) while another Division might stand one 4-h watch each 16 h (1 in 4). The reasons for this are discussed in Section 3.4. Thus, the membership of the team on watch, operating the cutter, varied from watch to watch.

The genesis of the traditional 4-h watch in marine operations is obscure. However, it is likely that it came into use because it meets several criteria: (1) 4 h is a factor of the 24-h day, (2) 4 h is a factor of an 8-h work day, and (3) 4 h is viewed as a length of time during which one can stand upright without excessive fatigue. Most crew members in this investigation reported standing 4-h watches on 1 in 3, 1 in 4 or 1 in 5 schedules.

Concerning criterion 1, being a factor of 24 h, it is quite difficult to design and maintain a work-rest schedule based upon shift lengths that are not factors of the 24-h day, such as 4, 6, 8 and 12 h (Miller, 1992). Thus, a 4-h shift length helps create a shift schedule that is simple to understand, plan and execute. As to being a factor of an 8-h work day, errors tend to increase disproportionately if one continues to perform physical labor beyond 8 h per day (cf. Grandjean, 1982). This latter observation has existed in the work research literature for decades and may have been self-evident long before that. Thus, carrying three teams on board may meet a minimum criterion for fatigue and error production: with two teams on 12 h of work per day, too many errors might occur due to fatigue. The use of four teams to reduce fatigue effects would present other problems: with four teams working 6 h per day, or working 8 h per day and taking one day in four off, crew members would probably become bored and inefficient. Also, the ship would need to carry supplies for 1.3 times as many people as it does for three teams.

The use of three teams instead of four carries with it a relative workload penalty. In industry, an 8-h system is staffed with four crews so that one crew is in recovery (days off) at all times. Thus, a 3-crew, 8-h maritime watch system calls for more work per unit time from a watchstander, by a factor of 1.3, than the standard, industrial 4-crew, 8-h system.

Finally, standing a watch often entails *standing* during the entire watch. This appeared to be true for Quartermasters, in particular, during this investigation (interestingly, helmsmen were seated in two of the six cutters observed). Certainly, there is historical precedent for seamen literally *standing* a watch. Whatever the reason, standing for four hours and then taking an 8-hour break from constant standing is, obviously, more palatable than standing for eight hours without a break. Whether or not four hours is a reasonable amount of time to stand depends in part upon the leg muscle tone and cardiovascular capabilities of an individual, but it is a physically demanding effort, particularly in high sea states.

In its favor, the 4-h watch can lend itself to a physiologically-regular work-rest schedule. A 1-in-3 or 1-in-6, 4-h watch schedule causes the person to start watches at the same time every day. This is good for maintaining the synchronization of the body's circadian rhythms with the day-night cycle. However, that regular-schedule advantage was usually lost onboard the cutters we observed. It was lost because, when enough qualified personnel were available in a division, the personnel shifted from 1 in 3, 4 h watches to 1 in 4 and 1 in 5, 4 h watches. Some were even able to shift from 1 in 6 to 1 in 7, 4 h watches.

The physiological aspects of shift work scheduling are apparently not the factors that most people use when given a choice of schedule. Sociological factors seem to be perceived as being more important. For example, many nurses prefer 3-crew, 12-h rotating shift systems to 4-crew, 8-h rotating shift systems because the former allow the creation of much longer periods of good quality time off than the latter (Miller, 1992). Cutter crew members we spoke with appeared to prefer slipping from 1 in 3 to 1 in 4 and lower ratios because the longer time between watches for the latter schedules allowed more time for both collateral duties and recovery sleep between watches. The crew members did not seem to appreciate the physiological advantage of keeping their watch schedule aligned with the day-night cycle: i.e., avoiding symptoms like those associated with jet lag.

3.0 METHODS

3.1 Conceptual Framework for Fatigue Assessment

The framework described here allowed us to consider the relationships among a number of contributors to fatigue. These contributors included both physical and mental stressors and work-sleep schedules. They also included the effort with which the individual responds to the stressors, including the individual's general level of motivation and the physiological and mental costs of the effort. The framework also allowed us to consider the quality of performance displayed overtly by the individual and the degree of fatigue experienced covertly.

3.1.1 Workload (Stress) and Effort (Strain)

The workload demanded of a crew member was viewed as a stress, to which the crew member would respond with some evidence of strain. An example of a physical stress would be the *requirement* to maintain a standing position in a heavy sea state. An example of a mental stress would be the *requirement* to navigate the ship safely within a fishing fleet, avoiding collisions. We attempted to differentiate physical (muscular) stress from mental stress. An example of strain in the physical domain would be the metabolic *effort* required to maintain an upright position in a heavy sea state. An example of strain in the cognitive domain would be the mental *effort* required to navigate the ship within a fishing fleet and avoid collisions. The degree of effort brought to bear on a specific work demand was assumed to be modulated by motivation. Specifically, greater motivation was expected to lead to greater efforts.

There are physiological costs associated with physical effort. Physiological costs are metabolic in nature and may include elevated whole-body metabolism associated with non-sedentary work loads, high levels of specific muscle anaerobic metabolism associated with lifting or with the maintenance of a single posture for a long time, relatively high myocardial metabolic demands due to the combination of poor physical conditioning and high physical workloads, and increased potential for the triggering of central nervous system sleep systems (falling asleep on the job) associated with sleep disruption (e.g., Hale, Hartman, Harris, Miranda, & Williams, 1973; Hale, Storm, Goldzieher, Hartman, Miranda, & Hosenfeld, 1973). Similarly, there are also psychological costs associated with effort. These include loss of motivation, feelings of anxiety, sleepiness and boredom, and loss of vigilance capability.

3.1.2 Performance

Performance is often the "bottom line" of the measures of interest in fatigue studies. For example, there was a desire in this study to learn if patrol tasks could be accomplished acceptably and safely. Performance measures may include such things as aerobic and anaerobic work accomplished per unit time, numbers of messages created and their accuracy, numbers of navigation fixes taken and their accuracy, etc. For this study, crew member performance was measured indirectly by presenting and collecting data from computer tasks that were representative of the cognitive tasks required of crew members, but they were not directly associated with cutter operations. These performance tasks all used visual stimuli.

Unfortunately, performance measures are not always sensitive to the effects of fatigue. This problem is due to the "two-edged sword" of human adaptability. The "good" edge is the ability of crew members to motivate themselves to face challenges and accomplish difficult tasks in acceptable manners in the presence of high levels of strain and resulting fatigue. Typically, the fatigued but motivated human can mobilize resources quite well for brief periods. However, the "bad" edge of the sword is the eventual effect of physiological and mental costs: there may be a catastrophic drop in performance or an involuntary onset of sleep (i.e., falling asleep on the job). Thus, the measured performance of the fatigued but motivated crew member may show no impairment at all until performance ceases abruptly.

3.1.3 Fatigue

Besides measuring performance, we wished to determine the degree of fatigue that physiological and mental costs had caused. The direct measurement of fatigue requires the collection of physiological indices such as electroencephalograms (brain waves) or assays of certain hormones from body fluids. Physiological measures had been discussed in the planning stages of the study, and were rejected by the project sponsor as being too invasive during cutter operations. Therefore, we elected to measure fatigue indirectly. Evidence of fatigue was sought in the perceptions of the crew members, in levels of task performance that were diminished below reasonable expectations, and in behaviors associated with sleepiness.

Fatigue may also lead to injury. An acute physical stress that exceeds connective-tissue limits may lead to a sprain or strain of a joint. Excessive aerobic effort, especially in a hot environment like an engine room, may lead to heat exhaustion and to myocardial ischemia, raising the possibility of heart muscle damage. The impairment of cognitive abilities may lead to poor risk-taking behaviors and subsequent accidents. For this project, we logged any incidents, such as personnel injuries or near-accidents associated with cutter operations, and attempted to collect information to determine whether the incident appeared related to fatigue.

We divided fatigue into three categories: circadian effects, acute fatigue, and cumulative fatigue. Circadian and circasemidian[5] effects usually produce relatively low mental and physical performance capabilities and extreme sleepiness during the pre-dawn hours, with a similar, but milder impairment during the mid-afternoon hours. This results in a predictable daily pattern of errors as shown in Figure 1. Acute fatigue was assumed to develop over the course of a single work period. Cumulative fatigue was assumed to develop across work periods when inadequate rest (sleep debt) was obtained from one day to the next. If inadequate rest is obtained over consecutive days, the sleep debt accumulates and can cause high levels of fatigue. A sleep debt can be repaid by obtaining additional (recovery) sleep. We expected circadian effects to be larger

[5] sir-kah-seh'mee-dee-an: an oscillation with a period of about 1/2 day, or 12 h

than cumulative and acute effects, and cumulative effects to be greater than acute effects (Wylie et al., 1996).

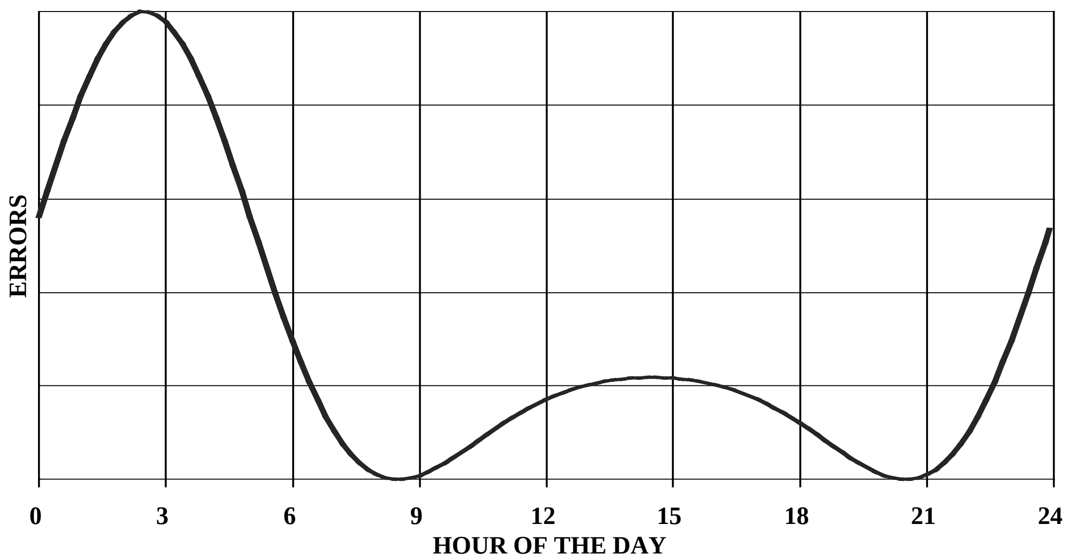

Figure 1. Circasemidian pattern of error occurrence. (Adapted from Mitler & Miller, 1996)

3.2 Research Design

There were no predetermined manipulations of work conditions aboard the cutters. This was an empirical, observational study, without intervention. We wanted to avoid the possibility of interfering with any potential emergency operations. We used descriptive statistics to summarize the data and sometimes used correlations to investigate relationships among measures, but inferential analyses (significance tests) were not performed in this observational study.

The investigation focused primarily on three Reliance class (210 ft; 64 m) medium endurance cutters (WMECs). The sponsors of the investigation felt that the limited crew complement of Reliance class cutters was likely to be more greatly stressed by high-tempo operations than the crews of the larger, high endurance cutters (WHECs). The baseline analyses on the three WMECs were supplemented by the analysis of one cutter in each of two additional vessel classes, the Bay class (140 ft; 43 m) ice-breaking tug (WTGB) and the Hamilton class (378 ft; 115 m) WHEC.

3.3 Scenarios

The intent was to focus on limited-duration, high-demand scenarios rather than on long-duration, low-demand scenarios. A patrol tends to be subdivided into longer-duration, low-demand scenarios punctuated by shorter-duration, high-demand scenarios with many "evolutions" (such as boardings, helicopter operations, search and rescue (SAR), etc.). According to the officers of the cutters used for the project, low-demand scenarios can nearly always be carried out safely and successfully if enough qualified people are on board to train the first-year crew members.

Unfortunately, despite the excellent scheduling efforts by various USCG commands, we observed no high-demand scenarios.

3.4 Study Participants

Crew member selection for this project was generally initiated by the cutter's Executive Officer (XO), assisted by Department Heads, and approved by the Commanding Officer (CO). The instructions to the XO were to provide to the principal investigator about 20 names of crew members. The sample was to include a distribution across the Departments, to be composed of about 2/3 watchstanders and 1/3 non-watchstanders, and to include several officers. There was no attempt to control the number of crew who stood different watches. Furthermore, it should be noted that even if two crew members had the same watch schedule (and even if they were both in the same department or division), they may not have had the same overall work-rest schedule because they may have been assigned to different non-divisional duties, such as being part of the fire-fighting team or a small boat crew. Thus, while the sample included both watchstanding and non-watchstanding crew, strict work-rest schedules were not controlled.

The principal investigator met with the potential recruits and explained the objectives and methods of the investigation and its potential risks and benefits. The volunteers' right to privacy and to withdraw from the investigation without prejudice were explained and questions were solicited and answered. Volunteers signed the informed consent form shown in Appendix B and provided witness signatures for each other. Volunteers also selected 4-digit personal identification numbers (PINs) that were used to encode their data for later processing and to help protect the crew member's privacy.

Data concerning crew member age and experience (Coast Guard, cutter, present job, etc.) were acquired for potential use as covariates in statistical analyses. In addition, data were collected concerning usual sleep and work schedules and sleep-related behaviors using a subset of a general sleep questionnaire developed by the Laboratory for Sleep, Fatigue and Safety.[6] This Background Questionnaire also allowed information about expected watch schedule, motivation and physical workload to be collected. Specific questions and responses from the questionnaire are cited in this report, as needed.

3.5 Qualified Personnel

The ratio of qualified to unqualified personnel within departments and divisions was an important factor in specifying watchstanding demands. When an insufficient number of qualified personnel were available to perform a specific job, then the qualified personnel moved from 1-in-3, 4-h watches to 6- or 12-h (port and starboard) watches, and they also were awakened from recovery sleep to perform portions of their job(s). On the other hand, we observed that when more than a sufficient number of qualified personnel were available to perform a specific job, then the qualified personnel moved from 1-in-3, 4-h watches to 1-in-4, 1-in-5, 1-in-6, etc.

[6] Mitler MM and Miller, JC, Department of Neuropharmacology, The Scripps Research Institute, La Jolla CA

We expected to encounter considerable variation in the distribution of qualified and unqualified crew members across departments and divisions on the selected cutters. We found that the definition of a qualified person was so complex in terms of schools and on-the-job training that the probability was near zero of accurately defining any specific mix. Each crew member must become qualified for work duties and watchstanding duties for their specialty within a division. In addition, each crew member must become qualified for duties outside their specialty, such as law enforcement (for boardings), fire fighting, and officer of the deck. These duties are assigned by "bills;" and the management of these bills is similar in concept to matrix management. We did discuss the mix issue with the officers of the selected cutters. They specified, to the degree possible, the existing problems with qualified-to-unqualified crew mixes, at the department level, the division level and bills aboard the cutter.

The effects of qualified/unqualified crew mixes could vary from scenario to scenario within a patrol because of the complexities noted, above. Thus, a division might not suffer from the mix problem during several days of high intensity boardings within a fishing fleet because that particular division's personnel weren't qualified to do boardings. However, in another scenario the division might temporarily lose personnel who were qualified to work in that scenario, leaving the division short of watchstanders. Thus, information acquired *a priori* did not reliably identify potential problems with qualified/unqualified mixes. The amount of information gained by measurement during the project was insufficient for the purpose of determining whether a specific department or division suffered as a result of its personnel participating in non-divisional duties such as boardings or fire-fighting team duties during helicopter operations. However, we noted that, when the helicopter was operating from a WMEC, approximately 80% of the crew was involved in direct support of the helicopter. This involvement included operations personnel on the bridge and flight deck, a small boat crew, a fire-fighting and rescue team and the tie-down crew.

One approach to the qualified-unqualified mix issue is empirical. One may examine crew members' time series of work and rest times. When the crew members show 1 in 3 watchstanding schedules, the division is adequately staffed. If they stand or they degrade to a port-starboard schedule, then the division is inadequately staffed. If they stand or they upgrade to schedules such as 1 in 4, 1 in 5, etc., then staffing is better than adequate. By this definition, better-than-adequate staffing was much more common on these cutters than inadequate staffing.

In addition to the watchstanding problem, a high ratio of unqualified to qualified personnel leads to another workload burden on both kinds of crew members: training. We noted this to be true especially for the last of our three WMEC patrols (D7#2, below). That patrol occurred just after the normal annual peak in permanent change of station orders, thus many new and younger personnel were on board. It also occurred after the ship had been in maintenance for three months. Training was especially intense during the first half of the trip. For example, the Chief Boatswain's Mate (BMC) promoted training of the young deck crew by conducting small boat launches and practice operations for large portions of two days early in the patrol. Similarly, many hours were spent in Marine Law Enforcement and other classroom sessions. When crew members received training for non-divisional duties such as law enforcement, more work time was needed to complete ship’s work (cleaning, preventive maintenance, administrative duties) each day or to make it up on subsequent days, and less waking rest time was available.

3.6 Sleep and Workload Measurement

During this project, crew member sleep and workload were two sides of the same coin. If one were to design a work-rest schedule based solely upon the adequate daily recovery (i.e., sleep) of human resources, then the amount of sleep acquired by workers would be somewhat independent of the amount of time spent working. The single, major, allotted sleep period for each crew member might be set, for example, at the 99th percentile of the average sleep requirement for 20-29 year old males (i.e., about 8 h). However, these cutter crew members’ shipboard work-rest schedules were determined by operational demands, shipboard job and task designs and the amount of available human resources. Thus, the opportunity for a crew member to acquire sleep was limited by the amount of work to be done. Because of that interdependence, several of our sleep measures and our workload measures were examined together as determinants of the work demand placed upon the crew member.

Watch schedules and their impacts on human circadian and circasemidian rhythms have very large effects on individual workload, effort, and performance. One aspect of these effects is that the level of crew member alertness and performance is governed strongly by the amount and quality of rest acquired before and between periods of work. There are three major determinants of sleep tendency during a period of intended wakefulness, (1) circadian effects, (2) the amount of preceding sleep and (3) the length of time since the last sleep period. In addition to the well-known circadian effect of high sleep tendency during the typical sleep period for humans from midnight until dawn, the amount of sleep a person has obtained in the preceding 24 to 48 hours is an extremely important determinant of sleep tendency during a period of intended wakefulness. Thus, it is necessary in any investigation of worker fatigue that we document both the time of day that work takes place and the time and amount of sleep obtained preceding each work period.

To accomplish this objective, we used the Crew Member's Daily Log (Appendix C) for key personnel. The Daily Log was an integration of a fatigue questionnaire created by the Laboratory for Sleep, Fatigue and Safety and the Mariner’s Daily Log created for commercial maritime operations (Sanquist et al., 1996). The Crew Member’s Daily Log provided information about the crew members’ daily cycles of work, rest, and sleep, as well as other information. It documented varying work-rest cycles and helped pinpoint obvious circadian disruptions of sleep patterns. The date- and time-stamped work-rest data in the Log were entered manually into spreadsheets for data selection and display. In addition, the Quartermasters’ Log - Weather Observation and Operational Summary Sheet (Form CG-4380B, Rev.3-67 and Rev. 4.95) provided us with daily and hourly weather and sea state data.

Cumulative sleep debt was estimated from the crew members’ reported times in bed, recorded in the Daily Log, compared to their reported ideal sleep lengths reported in the Background Questionnaire. The background question asked was, “What is your ideal nightly sleep length to keep you alert at work? _____ hours _____ minutes.”

Using reported times in bed tends to overestimate slightly the amount of time spent asleep because less time is spent sleeping than is spent in bed. However, the fatigued individual will sleep about 98% of the time spent in bed (Mitler et al., 1997). Each day (noon to noon) that a crew member acquired less than his or her self-reported ideal amount of sleep, the deficit was added to his or her cumulative sleep debt. Generally, these sleep debts were made up while underway.

We also searched for instances in which an individual received fewer than 5.5-h of sleep in the noon-to-noon period. Research indicates that this is the average point at which emotional and attitudinal problems begin to appear (Friedmann, Globus, Huntley, Mullaney, Naitoh, and Johnson, 1977; Horne and Wilkinson, 1985; Johnson, 1975).

For the day worker in *siesta* societies (i.e., nearly all present-day Mediterranean, Central and South American and Asian societies), an afternoon nap is expected and encouraged. The circasemidian pattern of both sleep and error tendencies (Figure 1) indicates that the afternoon *siesta* is part of normal human physiology (Mitler & Miller, 1996; Folkard, 1995). Properly structured naps appear to enhance subsequent crew performance (Rosekind, Graeber, Dinges, Connell, Rountree, Spinweber, & Gillen, 1994). However, a *siesta* was definitely *not* part of the daily underway schedule on the cutters observed in this study. When crew members on a cutter underway take more than one sleep per day, it is because they must recover from a demanding work-rest schedule, but do not have the time to do so within a single allotted sleep period. Using the Daily Log, sleep periods of more than one hour and separated by at least one hour were counted for each noon-to-noon period.

Metabolic task descriptions allowed rough estimates of the metabolic demand placed upon the crew member by the job. The crew member provided specific information in the Background Questionnaire about the tasks that made up their job(s). The metabolic demand of a job was approximated as work in watts (w) by reference to Table A-4 in Appendix A, and expressed as energy expenditure (power) in watt-hours once the time spent in each physical activity was recorded.

Ship motion was described in terms of: (1) swell and wind wave height data taken from the log, Weather Observation and Operational Summary Sheet, kept by the Quartermaster on the bridge, and (2) perceptions by the research personnel, reflecting a combination of their own and the crew members' reported experiences.

Engine room dry bulb temperatures were acquired sporadically for the latter two WMEC patrols, which occurred in a tropical climate in warm weather. When recorded, these data were recorded hourly by the ships' Engineering Departments in accordance with published instructions (COMDINST M6300.9 and M6260.17). For the second of these two patrols, wet-bulb globe temperature (WBGT) was acquired for the engine room on one occasion. The WBGT measure is far more relevant to human heat exchange properties than is the dry-bulb temperature.

Crew members provided ratings of perceived workload. We used a perceived physical exertion scale (Borg, 1985) and a perceived mental workload scale (AFFTC modification of the

USAFSAM workload scale; Ames & George, 1993). We also used a rating scale for motion discomfort based upon previous work by Wiker, Kennedy, McCauley, and Pepper (1979). All of these scales were incorporated into the Daily Log.

To allow an assessment of crew member motivation, two questions were asked on a Background Questionnaire and two on the Supplemental Questionnaire.

3.7 Performance Measurement

The use of computer-based performance tasks provided more detailed information than that which was available from operational tasks. For example, the computer-based tests allowed more frequent measurements than casualty drills. Several measurements were acquired per day instead of several per patrol. Additionally, the computer-based performance tests can allow assessments of speed-accuracy trade-offs in performance. Those trade-offs are not apparent in operational data. Each crew member provided data from several tasks, the descriptions of which follow.

Code substitution performance required competence in visual search mechanisms, encoding of data, decoding of data and rote recall. Pattern matching performance required competence in visual pattern recognition and spatial memory and probably assessed crew members' abilities to use a pattern-matching approach to failure diagnosis. The crew members' vigilance performance, producing measures related to keeping watch in a boring environment, were assessed. Visual temporal acuity was assessed using a simultaneity task. Finally, we assessed fundamental tapping speed.

The code substitution, pattern matching, simultaneity and tapping tasks were supported by a testing system implemented on a laptop computer. The FIT device, described below, was also controlled by one of the laptop testing systems. The Psychomotor Vigilance Task (PVT) was a battery-operated, hand-held, stand-alone device.

There was a measurable impact of the introduction of the computer-based performance testing on the workloads of the participating crew members. The context for assessing that impact encompassed at least two important factors. First, Coast Guard crew members had no regulatory limits set on the amount of hours which could be spent per day, or other unit time, in work or watchstanding duties. Thus, there were no regulatory duty time limits to be exceeded by introducing performance testing into the crew members' daily schedules. This was unlike investigations of civilian maritime operations (Sanquist et al., 1996) and commercial interstate truckers (Wylie et al., 1996).

Second, the participating crew members were instructed that duty requirements had priority over the computer-based performance testing. They also were instructed that sleeping was an acceptable alternative to performance testing if the individual felt that sleepiness and fatigue were becoming risk factors for the safe performance of his or her duties. They were asked to provide data about test sessions that were scheduled and then missed due to duty and sleep conflicts and to memory lapses. There was no physical workload associated with testing. The impact of testing was in the domain of cognitive workload and may have caused occasional sleep loss.

3.8 Circadian Rhythms

Circadian rhythm alignment (with the day-night cycle) of body temperature (T_{body}) was measured in crew members by self-measurement, also called autorhythmometry. The crew members measured their body temperature periodically during their waking hours using the eardrum (tympanic membrane) temperature as determined by an infrared ear probe now popular in homes and clinics (Thermoscan Pro-1; Beach & McCormick, 1991; Smith & Fehling, 1996).

The assessment of circadian rhythm alignment allowed us to determine whether or not a crew member might be suffering from a jet-lag-like malaise caused by a work-rest schedule that was not aligned with the day-night cycle. The lack of alignment and possible presence of malaise would be shown by a relatively flat amplitude and/or by a shift of the peak of the T_{body} rhythm away from the late afternoon-early evening period.

3.9 Acute Fatigue

The word “acute” is used in this report in its medical connotation, suggesting a brief occurrence of a condition (for example, one work period). Often, pre-to-post-watch and -work changes in perceived fatigue or task performance have been used to seek evidence of acute occurrences of fatigue.

For this project, we focused mainly on the detection of circadian effects and cumulative fatigue and less on the detection of acute fatigue. There were two reasons for this particular emphasis. First, it is clear that a work period or watch period will induce some degree of acute fatigue in the cognitive, physical or both domains and that physiological and psychological costs are unavoidable during work. Second, the degree of acute fatigue often is small, producing a relatively unreliable statistic. Thus, the reliable quantification of acute fatigue can easily become a futile effort.

Acute fatigue effects were estimated using a subjective rating of sleepiness, the Stanford Sleepiness Scale (SSS; Hoddes, Zarcone, Smythe, Phillips & Dement, 1973). Ratings were provided before and after work periods, watch periods and major sleep periods.

3.10 Cumulative Fatigue

Multiple daily subjective estimates of sleepiness were acquired at the performance testing station using a 100-point, visual analog scale called the Scripps Visual Analog Sleepiness Scale (SVASS). Cumulative fatigue was estimated as the straight-line (rectilinear) change across days of data collection for performance measures and for the SVASS.

The Epworth Sleepiness Scale (ESS) was used once at the outset and then twice on a 10-day cycle at the beginning of the Daily Log. Ratings above 15 out of a possible 24, which indicate a moderate to high likelihood of falling asleep, would be a cause for concern with respect to acceptable job performance. While the frequency of ESS data was insufficient for establishing cumulative fatigue, it was expected that changes in the SVASS would be similarly reflected in the ESS.

Instances of recovery sleep reflected the impact of cumulative or acute fatigue or both. As with sleep debt, recovery sleep was estimated from the crew members’ reported times in bed (Daily Log), compared to their reported ideal sleep lengths. Recovery sleep was defined in this study as the sleep lengths that exceeded a crew member’s estimate of his or her ideal sleep length. For example, a reported time in bed of 8 h and an ideal sleep length of 7 h 30 min would indicate 30 min of recovery sleep. Again, this approach tended to overestimate the amount of time spent asleep because less time is spent sleeping than is spent in bed, but the fatigued, normal individual will sleep about 98% of the time spent in bed. Recovery sleep served to “reset” the accumulation of sleep debt.

A physiological assessment of arousal based upon baseline pupil size was acquired using an oculomotor tester called the FIT 2000 (Pulse Medical Instruments, Inc., Rockville, MD). We expected to find cumulative fatigue effects expressed as gradual reductions in baseline pupil size and saccade (eye movement) velocity.

3.11 Training and Testing Schedule

3.11.1 Training

Each subject participated in one training session with either Dr. Miller or Matthew Smith at their assigned testing station. During this training session the subject’s personal identification code was initiated on the computer systems and specific training was given on each task.in the PATSYS computer based performance battery. Second, they were shown the use of the PVT, and given a one-minute sample test. On the ships where FIT data were collected, the subjects received training at the FIT testing station. One goal of the training session was that the subjects become capable of starting and performing all the required tests without supervision.

3.11.2 Testing

Number of tests per day: Our goal was to maximize the number of subjects' tests per day without interfering with their work and rest schedules. Since the schedules of crew members varied greatly within and across subjects, there was not a set time at which the subjects were asked to test. Rather, we tried to work out the best possible testing schedule on an individual basis, taking into consideration each particular subject's work/watch schedule. Subjects were asked to test three or four times per day, preferably not at the exact same time every day (to achieve a wider time of day variance with which to gauge circadian rhythm effects). This variability proved to be a natural consequence for most watch standers because their watch times rotated daily. The subjects were encouraged to test before and after watches, and at least one other time during the day – again, each subject according to their schedule.

Ideal test schedules (encouraged test schedules)

- Non-watch stander – before work, after work and one or two more times in the evening

- 1 in 3 watch – non-rotating schedule, with 2 watches and 1 work period any given week-day. Test before morning watch or work, after watch, after work or before 2nd watch and after 2nd watch. Weekends- before and after each watch period

- 1 in 4 / 1 in 5 watch – rotating watch schedule- before and after watches and work periods where possible.

- 1 in 6 watch – non- rotating schedule with 1 watch and 1 work period any given week-day. Before after watch, before or after work, and one other time during the day.

- 1 in 7 or higher – before and after work and watch and another time during the day

Order of testing

The subjects were free to choose the order of testing, being either the PVT or the computer-based PATSYS tests. The FIT testing always came after the PATSYS tests. This flexibility was given in an attempt to alleviate queuing at the testing stations.

3.12 Summary of Measures

Work Demand

- Work-rest schedule (Daily Log)
- Cumulative sleep debt (Daily Log, Questionnaire)
- Number of sleep periods per day (Daily Log)
- Task descriptions of metabolic demand (Daily Log, Questionnaire)
- Description of ship motion (ships' logs)
- Perception of motion discomfort (Daily Log)
- Engine room temperatures (ships' logs)

Effort

- Perceptions of physical and mental workload (Daily Log)
- General motivation (Questionnaire)

Performance (overt)

- Operational task incidents (observation)
- Computer-based performance tests (simultaneity, vigilance, pattern recognition, code substitution, tapping speed)

Fatigue (covert)

- **Circadian Effects**
  - Body temperature rhythm (Thermoscan)
  - Task performance rhythms (simultaneity, vigilance, pattern recognition, code substitution, tapping speed)
  - Sleepiness rhythm (SVASS)
- **Acute**
  - Stanford Sleepiness Scale (Daily Log)
- **Cumulative**
  - Perception of sleepiness (SVASS)
  - Combined sleep debt and recovery sleep pattern (Daily Log, Questionnaire)
  - General level of arousal (FIT 2000)
  - Computer-based performance task data (simultaneity, vigilance, pattern recognition, code substitution, tapping speed)

4.0 FINDINGS AND DISCUSSION

The findings of this observational study are given and discussed briefly in this section. A more detailed elaboration of the findings is given in Appendix F. After describing the patrols and crew members, the findings are presented in the following order: workload (stress), effort (strain), performance, and fatigue. Then the findings are summarized.

The descriptive data are presented here as means plus and minus (±) one standard deviation. Assuming a normal distribution, the plus-minus range of the standard deviation encompasses approximately the middle 68% of all crew members. The plus-minus range of twice the standard deviation normally encompasses approximately the middle 95% of all crew members.

4.1 Patrols

Data were acquired from the vessel types and at the locations shown in Table 1. More details, including underway condition, sea state, ship motion and operations, are shown in Tables D-1 through D-5 in Appendix D. A pilot study was conducted on a WMEC in District 13, patrolling the Washington-Oregon Coast (WOC). The pilot study data were used to revise data acquisition procedures. The data from the pilot study were reviewed and summarized in a preliminary letter report. These data were not relevant to the analyses presented here and are not included in the present report.

Table 1. Cutter types and patrol locations.

Vessel	***Location***
WHEC	D-17, Alaskan Patrol (Bering Sea)
WMEC	D-13 (WOC)
WTGB	D-9, Great Lakes (St Mary’s River)
WMEC	D-7 (Caribbean)
WMEC	D-7 (Caribbean)

The WMEC data were acquired from portions of three patrols. The first occurred in District 13, along the Washington-Oregon Coast, at the beginning of a patrol in the fall (WMEC-WOC). The main cutter activities included National Oceanographic and Atmospheric Administration (NOAA) buoy repair, fishery patrol, and search and rescue (SAR) standby. The second WMEC patrol segment occurred in District 7 in the Caribbean in the middle of a summer patrol (WMEC-D7#1). The main cutter activities included law enforcement boardings associated with drug interdiction, and SAR standby. The third WMEC patrol segment occurred in District 7, also in the Caribbean but at the beginning of a summer patrol (WMEC-D7#2). Again, the main cutter activities included law enforcement boardings associated with drug interdiction, and SAR standby.

The WHEC data were acquired during the second half of a District 17 Alaskan patrol (AlPat) in winter in the Bering Sea. The main cutter activities during the WHEC-AlPat included fishery patrols around the Aleutian Islands and along the Convention Line between Russia and Alaska, and SAR standby during the end of crab season.

The WTGB-D9 data collection period occurred at the end of the ice season in the 70-mile long St. Mary's River, between Lake Superior and Lake Huron, primarily between the Soo Locks at Sault Ste. Marie, Minnesota, and Lake Huron. The cutter had been breaking ice in the river daily for several weeks prior to the annual opening of the locks and continued to do so through the data collection period. The ice thickness ranged from approximately 8 to 18 inches. The freezing degree-day count[7] was about average for the area. The primary activities of the cutter during the period of observation included ice maintenance, ice flushing, escorting laker ore carriers and tankers in the river, and field maintenance on buoys. No direct assists of beset vessels were carried out during the observation period.

4.2 Crew Members

Demographic information about the crew members who participated in the study, including rank or grade, department, division, and watch schedule, is shown in Tables E-1 through E-5 in Appendix E.

There were no apparent biases with respect to rank and grade, duties and rates, gender, age, departments, or watch schedules in the withdrawals of crew members from those recruited nor from the subset who provided data. There were no obvious sleep pathologies detected among the crew members who filled out Background Questionnaires. Means and standard deviations were almost always based upon moderate sample sizes of 50 or more crew members. Thus, it appeared that the crew member sample was large enough and representative enough of the population of key crew members on the selected cutters to provide adequate descriptive data for those cutters.

4.3 Workload (Stress)

4.3.1 Hours of Work and Watch

On the average, watchstanders worked about 1.16 times as many hours per day than did non-watchstanders. Watchstanders worked a total of about 9.67 ± 2.22 h, including watch periods and workday hours, and non-watchstanders worked about 8.28 ± 2.0 h. Both means were somewhat high when one considers that (1) holidays and port calls were included in these

[7] Freezing degree-day formula: $\sum_{n=1}^{365}(t_{mn} - 32° F), t_{mn} < 32° F$

averages, and (2) about 16% of these crew members (by extension of the mean and standard deviation) worked an average of 11 hours per day (watchstanders) and 10 hours per day (non-watchstanders) and more.

4.3.2 Hours of Sleep

The mean reported sleep length (time in bed) was 7.46 ± 1.10 h. Based on these data and estimates from a normal probability distribution, approximately 16% of the time, the sleep length would be less than that at one standard deviation below the mean, $(7.46 - 1.10 =)$ 6.4 h. Generally, sleep researchers prefer to see sleep lengths at or above 7.5 hours to help assure that work is performed safely (Mitler et al, 1997). If about 16% of the average daily sleep length was less than 6.4h, as estimated here, there may be minor cause for concern..

The mean *ideal* sleep lengths reported by the crew members was 7.22 ± 1.11 h. This value was comparable to other reports. For example, Mitler et al. (1997) reported a value of 7.2 ± 1.2 h for commercial truck drivers at home. The crew members' mean *difference* between ideal sleep length and the mean daily sleep length (time in bed) acquired was $+0.23 \pm 1.20$ h. This positive difference indicated that, on the average, crew members acquired about a quarter hour more sleep per day aboard ship than their ideal sleep length at home.

While the average amount of sleep (time in bed) obtained by crew members appears to be within the normal range, the pattern of daily sleep shows a slowly but steadily accumulating sleep debt during the weekdays at sea, with recovery sleep occuring during holiday routines and in port (see Appendix Section F.15). Because there is not an accepted method for combining sleep debt and recovery sleep, sleep debt will be considered separately (see Appendix F for more details on recovery sleep). The mean, accumulating sleep debt was -0.64 ± 0.66 hours per day, or about 40 minutes per day. This accumulating sleep debt, calculated independently from actual occurrences of recovery sleep, revealed to some degree the negative effect of the work-rest schedule on crew members' abilities to generate adequate amounts of sleep. In other words, if the work demand had remained the same as it was in these low-tempo operations and recovery sleep had been unavailable, as may be true during high-tempo operations, this gradual, cumulative, daily increase in sleep debt would have begun to negatively affect crew member emotions and attitudes after about two days.

We compared the mean daily hours of sleep acquired by 42 watchstanders (7.3 ± 1.1 h) to the mean daily hours of sleep acquired by 13 non-watchstanders (8.0 ± 0.7 h). These means were reliably different ($p < 0.05$, 2-tailed t-test).

4.3.3 Numbers of Sleep Periods

We compared the mean daily number of sleep periods used by the 42 watchstanders (1.22 ± 0.19) to the same measure for 13 non-watchstanders (1.12 ± 0.13 h). These means were marginally reliably different ($p < 0.09$, 2-tailed t-test). These values were comparable to the 1.18 sleep periods per day of commercial truck drivers operating mainly on highly irregular work-rest schedules (Mitler et al., 1997). The highest numbers of crew member multiple sleep periods tended to occur while underway. This was consistent with the requirement to stand underway watches and the practice of using a small duty crew when the ship was tied to a dock.

4.3.4 Metabolic Rate

Watchstanders expended slightly (11.5%) more energy per day than non-watchstanders. Both watchstanders and non-watchstanders expended energy at about the same rate while on watch and at work. This range fell between the average energy expenditure rates for sitting and standing. About 16% of the watchstanders expended energy during the work day at approximately the same rate as standing. Though high-demand physical labor occurred in some cases aboard the cutters, it was usually of such brief duration that it did not drive the average energy expenditure rates very high.

4.3.5 Ship Motion and Motion Discomfort

There were about 11 days of significant motion out of about 67 days underway aboard the three WMECs and the WHEC-AlPat. The WTGB-D9 operated in ice at all times. Thus, sea and swell waves were nearly absent and ship motion was negligible aboard the WTGB.

During the pilot study, WMEC-WOC and WHEC-AlPat patrol segments, we noted a common strategy used by the COs to deal with the effects of ship motion. In the pilot study and the WMEC-WOC patrol segments, the cutters steamed directly north-northwest from San Francisco Bay toward the WOC patrol area, and from Astoria, Washington southwest toward a NOAA Buoy, respectively. There was a great deal of ship motion in the vertical axis due to the combination of pitch and heave.

The linear component of pitch, a function of distance from the center of rotation of the ship, combines with heave to yield the total vertical acceleration at any location aboard the ship. This combined vertical motion of ship motion is experienced by a crew member as whole-body oscillation in the z-axis (spinal axis) while standing or seated. It is known from controlled studies in a sea-motion simulator that z-axis oscillation at frequencies of about 0.2 Hz (a 5-second period), is particularly conducive to motion sickness (Guignard & McCauley, 1990; McCauley, Royal, Wylie, O'Hanlon, & Mackie, 1976; O'Hanlon & McCauley, 1974). Consistent with the model, many crew members suffered from overt motion sickness under these conditions.

However, when a cutter was patrolling an area, as opposed to steaming toward a specified destination, the CO often turned the cutter into the trough of the swell. This traded pitch for roll, which results in a reduction in the average vertical (z-axis) amplitude (except for crew members at the center of rotation of the vessel). Under these conditions of reduced pitch but increased roll, there appeared to be a reduction in anecdotal reports of motion sickness.

Anecdotal reports indicated that this apparent reduction in motion sickness frequency occurred at the expense of increased sleep disruption, due to rolling in the bunk, and increased physical strain as crew members tried to remain standing, walking and sitting upright on a rolling surface. During the WMEC-WOC patrol segment, during days of significant motion, rolls of ±20° were observed on the bridge inclinometer. Significant physical effort is required to work successfully with this degree of roll.

Sleepiness is a common symptom of motion sickness and is called the “sopite syndrome.” Also, a common side effect of most motion sickness medications is sleepiness. For these reasons, there was probably a relationship between motion discomfort and the scheduling of major sleep periods for susceptible crew members.

Several underway investigations of the effects of motion and motion sickness have been performed. In a Coast Guard study comparing a Small Waterplane Area Twin Hull (SWATH) vessel to a 95’ Patrol Boat and a 378’ WHEC, significant levels of motion sickness, stress, mood deterioration and performance decrement were found in the Patrol Boat due to the vessel motion (Wiker, Pepper, & McCauley, 1980). A review of the effects of motion and motion sickness concluded that there was no solid evidence for reduction in central nervous system function due to motion sickness. The highly motivated individual continued to perform cognitive and perceptual tasks at normal levels even when seriously sick, up until the moment of vomiting, when task performance normally ceased, at least temporarily.

The direct biodynamic effects of vessel motion, however, are known to degrade manual performance independent of motion sickness (Hettinger, McCauley, & Kennedy, 1990). Anecdotal observations on the 140’ ice-breaking tug, indicated that the vibration caused by the ice-breaking action of the ship in 8-18-inch ice disturbed fine-motor activities, such as writing and keyboarding, but not gross-motor activities, such as walking, except occasionally on the bridge.

Future investigations of cutter crew fatigue should examine more fully the effects of ship motion on crew members’ sleep patterns and perceptions of physical fatigue, and include accelerometer measures of the frequency and amplitude of ship motion in multiple axes, while assessing crew member energy expenditure rates and quantified sleep patterns.

4.3.6 Noise and Temperature

The data acquired from the ships’ own noise surveys were inadequate for the purpose of assessing the effects of noise stress on specific crew members’ cognitive functions and sleep. However, the estimated (from available survey data) average noise stress in often-used work and rest spaces near the engine room, where ear protection was seldom worn, approximated the upper limit (75 dbA) of the sound pressure levels generated by heavy highway traffic, on the highway. According to a general reference (Grandjean, 1982), this amount of background noise:

- Interferes with speech intelligibility,
- Raises blood pressure,
- Interferes with sleep,

- Interferes with cognitive processes, and
- May induce temporary hearing losses due to 24 h/day exposure times.

On the 140’ ice-breaking tug, noise caused by ice-breaking was probably below 80 dbA on the main deck and above. Below the main deck, it was probably above 80 dbA and all crew members wore ear protection. Since the ship operated only during daylight hours, ship motion, noise and vibration did not affect sleep quantity or quality except for naps taken during the day.

While there is a dichotomy in the requirement to wear hearing protection (worn when the ambient noise level is above 80 dbA), there is not a dichotomy in the continuous range of noise exposure on a cutter. Crewmembers complied fully with requirements to wear ear protection in identified hazardous noise spaces, but few wore hearing protection in other spaces. Even though the amount of engine noise in the non-hazardous spaces near the engine room was only about half the criterion level for wearing hearing protection (i.e., 75 vs 80 dbA), it was sufficient to interfere with speech communication, cognition, sleep quality, and, if sustained over long periods, to cause temporary hearing losses.

Subsequent fatigue investigations should incorporate dedicated sound pressure level measurements. These should be used to quantify the continuous noise stress experienced by individual crew members and to examine correlations with task performance and quantified sleep patterns.

The data acquired from the ships’ own temperature surveys were inadequate for the purpose of assessing the effects of temperature stress on individual crew members’ cognitive functions and sleep. In the two District 7 WMEC patrols, limited measurements by the crew indicated that engine room dry bulb temperatures averaged about 100 to 112° F, and the engine room Wet-Bulb, Globe Temperature (WBGT, see Appendix F) averaged about 90.5°. These temperatures approximate the upper permissible limit for light, sedentary work (Grandjean, 1982). We estimated, above, that the average physical workload of a crew member approximated light, sedentary work. Crew members’ physical work efforts exceeded this average about half the time. Thus, there may be the need to limit individual crew members' exposure to these high temperatures when there is a physical work demand greater than routine inspections.

If USCG guidelines are not available for work limitations in high ambient temperatures, there is a guideline available for light, moderate, and heavy work rates, showing 100%, 75%, 50%, and 25% exposure times for each work rate for temperatures from 75 to 90 degrees WBGT (Miller and Horvath, 1981, Figure 5.7). Above 90 degrees WBGT, not even light physical work is recommended. Thus, only routine inspections should occur when the engine room is above this temperature. If maintenance must be performed, then the engine room should be cooled. In emergencies, when engine room cooling is not possible, then medical preparations should be made to deal with possible heat stress reactions.

Subsequent fatigue investigations should incorporate dedicated temperature (WBGT) measurements in the engine room to quantify more exactly the heat stress experienced by individual engine room crew members during preventive maintenance and unscheduled repairs.

4.4 Effort (Strain)

4.4.1 Perceived Workload

The crew members perceived somewhat higher physical work demand during work periods (a mean rating of 4.5 ± 2.6 on the 15-point scale) than during watch periods (a mean rating of 3.8 ± 2.1). A rating of 4 on the physical workload scale was anchored to the phrase, “Very light.”

The crew members perceived somewhat higher mental work demand during work periods (a mean rating of 3.5 ± 0.9 on the 7-point scale) than during watch periods (a mean rating of 3.1 ± 0.8). A rating of 3 on the scale was associated with the statement, “Moderate activity; easily managed; considerable spare time.” A rating of 4 on the scale was associated with the statement, “Busy; challenging but manageable; adequate time available.”

These mean ratings of perceived physical and mental workloads were consistent with the resulting occurrence of mild fatigue.

4.4.2 Perceived Motion Discomfort

Perceived motion discomfort was recorded using a scale that ranged from 1 ("normal; symptom free") to 7 ("severe discomfort; I am unable to work"). Among the subgroup of our crew members who perceived some degree of motion discomfort, the experience was about the same during work, watch and major sleep periods. In each case, motion discomfort was rated at about 2.0 ± 1.0 on the 7-point scale. It was surprising that motion discomfort was not rated as being lower while lying down to sleep. We expected to see a much higher mean rating (i.e., lower level of discomfort) for motion discomfort associated with major sleep periods than with work and watch periods.

4.4.3 Motivation

Motivation is measured as an indicator of “effort,” which is the link between work demand, fatigue and performance. With four simple questions, we attempted to determine roughly how motivated the crew members were toward doing their jobs. A hint of a motivational problem was found in the range of responses to motivation question 3 (“For your country, this patrol has been…”): of the thirty respondents, ten chose a rating of 3 (borderline), one chose a rating of 4 (not important) and one chose a rating of 5 (very unimportant). The slightly low degree of importance attributed to the patrol probably reflected the fact that no high-tempo operations occurred during the observation periods. However, in general, the crew members tested indicated a relatively high motivation to perform their jobs.

4.5 Performance

4.5.1 Critical Incidents

We observed no involvement of crew members in the sample in critical incidents related to fatigue.

4.5.2 Vigilance Task

In the PVT, a lapse was a failure to detect an expected target in a timely manner (0.5 sec, in this case). The crew members' mean number of lapses per trial got slightly worse from day to day. Due to practice effects, one would expect the lapse rate to improve from day to day.

In a 7-day, in-laboratory investigation of reduced sleep, lapses increased at about twice the rate as it did for our crew members (Dinges, Pack, Williams, Hillen, Powell, Ott, Aptowicz, & Pack, 1997). The laboratory subjects' sleep durations had been cut to about 5 hours per night, which was about two-thirds of their habitual sleep length. The increase in the number of lapses was less severe for the crew members than it was for the sleep truncation subjects.

The overall mean of PVT lapses was nearly four lapses per trial. In alert, well-rested subjects, one expects an average slightly below one lapse per trial and after 7 days of sleep truncation to about 5 hours per night, one expects about 4 lapses per trial (Dinges et al., 1997). Thus, the mean PVT lapses in our sample of cutter crew members was nearly equivalent to test subjects with only 5 hours of sleep per night for 7 days.

The speed of responses for lapses decreased on all cutters. With practice effects, one would expect the speed to increase from day to day.In the 7-day, in-laboratory investigation of reduced sleep, the speed also decreased (Dinges et al., 1997). The mean daily decrease in the crew members' speed was more severe than that of the laboratory subjects.

The overall mean speed was about 0.43 sec. In alert, well-rested subjects, one expects an average around 0.33 sec, and after 7 days of sleep truncation to about 5 hours per night, one expects an average speed of about 0.45 sec (Dinges et al., 1997). Again, the crew members' lapse response speeds were similar to laboratory subjects who received only 5 hours of sleep per night for a week.

Though the crew members slept more than the laboratory subjects described here, their vigilance performance was similar. Since sleep quantity did not explain the similarity, crew member sleep quality was indicated as a culprit in producing the observed vigilance performance decrement. This is a testable hypothesis that simply requires the application of existing, quantitative sleep quality measurement tools (specifically, electrophysiological measures) and the PVT to crew members during patrols. Questionnaires are also useful, but do not specify the physiological nature of the sleep disturbance (cf. Sanquist et al, 1996). Without that information, prescritpive changes to sleeping behaviors and work rest schedules, with the intent of improving sleep quality, may be misdirected.

4.5.3 Tapping Task

Tapping was one of several performance tasks that were grouped together in the testing computer. The grouped tasks included tapping, simultaneity, code substitution, and pattern recognition. On the average, about 12 crew members per cutter provided good quality data on this task set. This was a very respectable participation rate.

Tapping speed increased on all cutters as one would expect with practice effects. The overall mean tapping speed was about what we expected (Kennedy, Turnage, Wilkes, & Dunlap, 1993; Kennedy, Turnage, & Dunlap, 1992). There was no evidence of fatigue associated with this measure of fundamental neruomuscular function.

4.5.4 Simultaneity Task

The mean simultaneity interval increased each day. This finding was consistent with the development of cumulative fatigue in visual temporal acuity. With practice effects, one would expect the simultaneity interval to become shorter from day to day.

4.5.5 Pattern Matching Task

Pattern matching throughput decreased from day to day on three of the five cutters (WMEC-D7#2, WHEC, WTGB), indicating that pattern matching performance became slightly worse from day to day. This finding was consistent with the development of cumulative fatigue in visual pattern recognition and/or spatial memory on those cutters. With practice effects, one would expect pattern matching throughput to increase from day to day.

4.5.6 Code Substitution Task

Code substitution throughput increased from day to day on all cutters as one would expect with practice effects. The mean for code substitution throughput was about what we expected (Kennedy, Dunlap, Turnage, & Fowlkes, 1993; Kennedy, Turnage, Wilkes, & Dunlap, 1993; Kennedy et al, 1992). There was no evidence of fatigue associated with this measure of cognitive function.

4.6 Fatigue

The SVASS scale ranged from 1 = “Wide awake,” to 100 = “Sleep onset soon,” with the middle of the scale (50) anchored with the phrase, “Losing interest in remaining awake.” The mean SVASS was about 42 on the 100-point scale. Thus, the crew members’ overall average level of sleepiness while on patrol was more closely associated with “losing interest in remaining awake” than with being “wide awake.” This was somewhat disturbing. We had expected to see a mean much farther below 50, i.e., closer to “Wide awake.” This result was consistent with a pervasive perception of sleepiness among crew members and with the vigilance decrement observed using the PVT.

4.6.1 Circadian Patterns

The mean body temperature did not differ significantly between watchstanders and non-watchstanders. However, the strength of the cycle differed significantly between watchstanders and non-watchstanders ($p = 0.03$). Watchstanding flatttened the circadian rhythm in body temperature by a factor of about 0.63. In other words, the circadian cycle of the watchstanders was only about 2/3 as strong as the non-watchstanders. This finding is consistent with a general malaise among watchstanders, including their reported feelings of sleepiness and their poor vigilance performance.

4.6.2 Acute Fatigue

Small, acute increases in subjective perceptions of sleepiness, around the 3 on the 7-point SSS, occurred in association with both work and watch periods, independent of the estimated cumulative fatigue and circadian rhythm effects. Conversely, small, acute decreases in subjective perceptions of sleepiness around the 4 on the 7-point SSS occurred in association with major sleep periods, independent of the estimated cumulative fatigue and circadian rhythm effects. The rating of 3 was anchored with the phrase, “Relaxed; awake; not at full alertness; responsive.” The rating of 4 was anchored with the phrase, “A little foggy; not at peak; let down.”

Ideally, one would prefer seeing ratings closer to 1 on the scale after major sleep periods and before work and watch periods. However, office workers rated themselves similarly to the crew members at the start and end of the office work day (using a similar scale) (Miller & Navarez, 1986). Thus, the overall degree of acute fatigue detected by the SSS was about that expected for office workers, i.e., mild fatigue.

4.6.3 Cumulative Fatigue

The SVASS and the ESS indicated almost no change in reported sleepiness from day to day. Specific days of increased recovery sleep suggested that, during port calls and during holiday routines while underway, many crew members acquired recovery sleep. However, on the average, adequate recovery sleep was acquired even while underway.

Useful oculometric data were acquired from eight crew members across three cutters. Two were watchstanders. The two watchstanders presented the worst day-to-day increases in fatigue indications of the group of eight crew members. Thus, while the SVASS and ESS data did not support an hypothesis of an accumulation of fatigue across the measurement period, the day-to-day changes in the following measures did support an hypothesis of an accumulation of fatigue: vigilance performance, temporal visual acuity, and pattern matching performance. This picture suggests that the abilities of the crew members to remain vigilant and to recognize system failures visually were declining slowly during the patrols, but that they were unaware of the changes.

4.7 Signs of Fatigue

A number of signs of fatigue and sleepiness were detected in the crew member sample, even though we observed no high-tempo operations. From means and standard deviations, compared to absolute criteria, we may make the following quantitative statements. The crew members worked an average (mean) 63-hour week, so about half the crew members worked more than that. About 9% of the crew members received six or fewer hours of sleep per 24-h period, placing them at a sharply increased risk of making errors of omission and commission. About 37% broke their sleep into multiple periods in a manner similar to long-haul truck drivers who acquired only about 5 h sleep per major sleep period. About 23% of the crew members experienced vigilance lapse frequencies similar to subjects sleeping only 5-h per night. The lapse reaction times of about 44% of the crewmembers were similar to those same 5-h sleepers. In round numbers, anywhere from 10 to 45% of the crew members displayed one or more of these signs of fatigue.

A greater proportion of the crew would suffer from fatigue, and the associated safety risks and decreased mission capability, under conditions such as high tempo operations, significant maintenance requirements, reduced crew levels, and/or sustained high sea states. We recommend further study of this potential problem based upon direct comparisons of fatigue and related measures before and after crew reduction.

5.0 CONCLUSIONS

Reviewing the above findings in the sequence suggested by the conceptual framework for fatigue (see section 3.1) -- work-rest schedule demand, effort, performance, and fatigue-- the following picture emerges. Watchstanders averaged about 9.7 hours of work per day while non-watchstanders averaged about 8.3 hours per day, across all patrol days. Industrial investigations have shown that errors tend to increase disproportionately after about 8 hours of work in one day (cf. Miller, 1992). Overall, the work schedule caused many crew members to work up to 1.75 times as many hours as they would, for example, in a classic 40-hour week.

Generally, the crew members acquired adequate sleep with respect to their self-reported ideal amounts, but the quality of that sleep was questioned for two reasons. First, the crew members tended to split their sleep into more than one period per day. Watchstanders split their sleep more than non-watchstanders and received less sleep. Splitting sleep is known to reduce sleep quality (cf. Mitler et al., 1997). Second, their average vigilance performance was somewhat impaired, suggesting a level of sleepiness similar to that of laboratory subjects sleeping only 5 hours per night for a week.

Although the crew members' vigilance was somewhat impaired, the types of tasks performed by the crew did not place a high physical workload demand on the crew, and thus, were not a likely source of sleepiness. Ambient noise levels and, for engine room personnel in D7, ambient temperature levels, may have contributed to crew member fatigue, but there were inadequate noise and temperature data to test this hypothesis. The crew members' data on perceived effort and motion discomfort suggested that neither high levels of mental workload, physical workload, nor ship motion were likely sources of the crews' level of sleepiness.

In terms of overall performance on the computer-based performance tasks, the crew members performed well except in the area of vigilance. Generally, vigilance tests are the most sensitive of computerized tests with respect to the detection of sleepiness and fatigue due to sleep disruption (cf. Mackie, 1977). Though the crew members' visual search mechanisms, encoding and decoding of data, rote recall, visual pattern recognition, spatial memory, visual temporal acuity, and fundamental neuromuscular coordination and speed all appeared to function normally, their impaired vigilance performance was of concern. Vigilance is the ability to sustain and focus attention in a boring situation, with the goal of quickly and accurately detecting the occurrence of rare, unpredictable, important events. Obviously, this capability applies to underway tasks such as the monitoring of radar, radio, engine and other systems and visual scanning by topside lookouts. Delayed or inaccurate detections in these areas can be problematic for cutter operations.

There was other evidence of crew member fatigue. First, their overall, average rating of sleepiness was very much closer to the description, "Losing interest in remaining awake" than to the description "wide awake." Second, the circadian rhythm of body temperature was somewhat suppressed in watchstanders. Third, the crew members reported approximately the same acute changes in sleepiness across single work and watch periods as office workers. Of course, the watch periods were only half as long as office work days, and the crew members worked more hours per day than office workers. Finally, even though vigilance performance, pattern matching performance and temporal visual acuity were approximately normal overall, they all declined from day to day. Crew members did not report perceptions of accumulating fatigue. However, people who are fatigued are often not accurate in assessing their state of alertness.

Among all of these observations, the effect of greatest concern for cutter operations is the somewhat degraded vigilance performance of the crew members. Likely causes for this impairment, within our set of measurements, included the average number of hours worked per day, the average number of hours of sleep per day, the average number of sleep periods per day, circadian rhythm suppression, daily changes in temporal visual acuity, and age. We examined the interrelationships across crew members among these measures and the vigilance measures. The results are shown in Table 2.

Referring to the Mean Strength column in Table 2, one sees that age had a greater association (0.34) with crew member vigilance performance than any other factor we examined. Interestingly, the age effect was opposite than one might guess. Greater age was associated with faster lapse response speed and fewer lapses. This may reflect a somewhat higher level of discipline for paying attention in the older members of this group, which ranged from 22 to 40 years in age (mean 29 years).

Table 2. Relative strengths of relationships (partial correlations) between several independent variables and the two vigilance variables (n = 30). The maximum range of a partial correlation is -1.0 to +1.0. The mean strength is the average of the absolute values of the two partial correlation values to its left.

Independent Variable	**Lapse Response Speed**	**Number of Lapses**	**Mean Strength**
Hours of Sleep/Day	0.23	-0.31	0.27
Number of Sleep Periods/Day	-0.16	-0.07	0.12
Body Temperature Rhythm Amplitude	-0.03	-0.03	0.03
Age	0.37	-0.32	0.34
Change in Visual Temporal Acuity	-0.23	0.14	0.18
Hours of Work/Day	-0.18	0.25	0.22

The number of hours of sleep acquired each day was second only to age in its association (0.27) with vigilance performance. As expected, more sleep was associated with greater lapse response speed and fewer lapses. The total number of hours of work and watch each day was ranked third in its association (0.22) with vigilance performance. As expected, more work was associated with slower lapse response speed and more lapses (i.e., poorer vigilance). The daily change in visual temporal acuity also showed a relatively large association (0.18) with vigilance performance. An increasing temporal acuity interval, which we interpreted as an expression of accumulating fatigue, was associated with declining lapse response speed and more lapses.

6.0 RECOMMENDATIONS

As just discussed, cutter crew members work significantly more hours per week than does the general population. Watchstanders in particular slept fewer hours, split their sleep, and had poorer quality sleep. Even though our data were collected during relatively low tempo operations, these crews exhibited signs of fatigue, including reduced levels of vigilance. High tempo operations would be expected to exacerbate these problems, since work-rest schedules would likely be altered, and total sleep achieved would probably be reduced.

In order for Coast Guard crews to be *Semper Paratus*, it is recommended that additional studies be undertaken to develop and implement a crew endurance management program for the Coast Guard. Such a program should take a look (at a minimum) at traditional cutter work-rest schedules, drill and training schedules, and sleeping accommodations to determine what types of changes might be made that would improve crew member sleep duration and quality without sacrificing mission requirements (for an example, see Comperatore, 1997). An effective crew endurance management program would also include training for crew members and commanding officers on the chronobiological and psychophysiological realities of fatigue and alertness, and on the types of countermeasures that individuals and departments can use to manage their level of alertness. Maintaining high levels of crew alertness and “readiness” needs to become as much a part of Coast Guard culture as maintaining its equipment and cutters.

Recommending how to develop a crew endurance management program is beyond the scope of this study. However, this study did elucidate two aspects of cutter life which appear to be detrimental to crew alertness, namely common watchstanding schedules and sleep schedules. Recommendations for improvements in these two areas are presented below.

6.1 Reducing Fatigue via Alternative Watchstanding Schedules

Watchstanders slept less, and split their sleep more, than non-watchstanders. Splitting (fragmenting) sleep into two or more periods is known to decrease the restorative value of sleep and produce fatigue. Cutter watch schedules were also influenced by the number of people in the department who were available to stand watch. This created schedules (such as 1-in-4 or 1-in-5) which required a watchstander to stand watch at different times from day to day. Such "rotating" work schedules often force daily changes to sleep schedules, disrupting the sleep-wake cycle. Such circadian disruption can produce fatigue and "shift-lag", because the body clock is no longer adjusted to a set sleep-wake schedule. Therefore, in order to prevent shift lag and provide more restorative sleep, we explored some possibilities for improved watch scheduling (see Appendix G for details). The recommendations are based on known principles of chronohygiene[8] (Hildebrandt, 1976).

The use of watch rotations that comply with the principles of chronohygiene, giving 24 h of recovery between night work periods and keeping the human circadian rhythm aligned with the day-night cycle (Hildebrandt, 1976), would ease the stress and strain experienced by watchstanders. Crews should consider the following alternatives to slipping from 1-in-3 to 1-in-4 and 1-in-5, or from 1-in-6 to 1-in-7. One alternative is the equivalent of a 1-in-6 watch schedule. That is, to rotate two teams (or two crew members) between the 1-in-3 schedule and non-watch work days. Thus, for example, an individual would stand a day of 1-in-3 watches, then spend a day at work only, then stand a day of 1-in-3 watches, then spend a day of non-watch work only, etc. Alternatively, watches could be stood for two or three days, followed by two or three days of non-watch work only.

In addition, there are many possible rotating-watch combinations that treat all personnel equally (Miller, 1992). The principles of chronohygiene and the basic arithmetic of rotating shifts was applied to the question of watchstanding to produce the alternative schedules that are shown in Appendix G. The Appendix shows alternatives for the present 1-in-3, 1-in-4 and 1-in-5 schedules. There are other possible alternatives, as well.

We note that the alternatives shown in Appendix G preserve the watch change time of 04:00. This is a good time to change watches. The watch-change activity helps to offset the expected drowsiness and high error risk associated with operations that occur at 04:00 (Mitler & Miller, 1996; Folkard, 1995).

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[8] The schedules provided in Appendix G are based on proven schedules from shiftwork environments. A follow-on research project will be developing and testing new schedules specifically for CG cutter crews.

6.2 Reducing Fatigue via Better Scheduling of Sleep

Crews should consider an alternative to the observed practice of using late sleeping for night watchstanders and encouraging late sleeping on Sundays by not piping reveille. Generally, late sleeping continued until 10:00. On holidays, Mess Deck activity was relatively absent until after 10:00, suggesting that late sleeping occurred until about 10:00 on those days as well. However, investigations of human circadian rhythms suggest that a constant waking time from day to day is a very strong time cue (*Zeitgeber*) that helps align the body's rhythm to the day-night cycle. Of course, alignment to the day-night cycle helps prevent the general feeling of malaise and other shift-lag symptoms, including an increased risk of errors.

It would be more appropriate for crews to establish a mid-afternoon *siesta* period for night workers and to encourage the *siesta* on holidays instead of late sleeping. The *siesta* would be in accordance with the biological circasemidian pattern of human sleepiness and error probability (Mitler and Miller, 1996; Folkard, 1995). The mid-afternoon "slump," when people feel sleepy and error risk is relatively high, is an unavoidable reality of brain biology. Crews should exploit this biological phenomenon to enhance productivity and reduce risk. Thus, reveille would be piped at the same time, seven days a week and a lights-out and quiet period would be created after Quarters each day for 3 h. In addition, the enhancement of education for crew members about the need for recovery sleep is indicated.

7.0 SUMMARY

This study established typical levels of workload, performance, and fatigue found in normal, daily Coast Guard cutter operations. Data were collected on three WMECs, one WHEC, and one WTGB for about twenty days each. Even though no high-tempo operations were encountered during the study, evidence of mild fatigue was observed in many crew members. While the overall duration of sleep reported by crew members appeared adequate, the quality of that sleep is in question, given that many crew members split their sleep into two sleep periods per day, a practice known to reduce the restorative value of sleep. Also, the average vigilance performance of crew members was reduced to a level similar to that found in laboratory subjects who have slept only five hours per night for a week.

While the findings do not pose grave problems for crew under normal operations, the levels of fatigue would be expected to be higher and a cause for concern under extended high tempo operations. Recommendations were given for increasing the general level of alertness among the crew. Watchstanders were found to sleep less and split their sleep more than non-watchstanders, and an examination of common watchstanding schedules used on board these cutters found that the schedules themselves would be expected to produce fatigue. Alternative watchstanding schedules were recommended which conform better to the principles of chronohygiene and provide recovery periods between day and night work. Taking afternoon naps for recovery sleep, rather than the present practice of sleeping late, would be another way to reduce fatigue without disrupting crew members' circadian cycles.

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APPENDIX A

ADDITIONAL INFORMATION ABOUT METHODS

A.1 Approaches to Observation

We considered several approaches that would allow us to acquire data during limited-duration, high-demand scenarios on the selected cutters. First, there was *manipulation*: We would specify scenarios to be enacted by the cutter and crew. The advantage of this approach was that the activities of the cutter and crew would be predictable, many extraneous variables would be controlled, and data collection would proceed efficiently. The disadvantages of this approach were: (1) the operations would be simulated, casting doubt upon the generalizability of the results to operational situations, and, (2) the cutter would not be available for regular duties.

Second, there was *reaction*: Our data collection crew would ride the cutter for about 20 days and collect data before, during and after naturally occurring, high-demand scenarios. The predictability of cutter and crew activities with this approach would be very low and data acquisition efficiency would be low. Finally, there was *knowledgeable*, *planned observation*: We would work with patrol schedulers to maximize the predictability of cutter and crew activities, especially law enforcement (LE) fishery boardings, search and rescue (SAR) and AMIO. We would be present to collect data before, during and after high-demand scenarios.

We used a combination of the reactive and planned observation approaches. This approach required the presence of a Data Acquisition Team (DAT) on each patrol. The nominal DAT consisted of one to two members of the primary research team supported by one or two Coast Guard Auxiliary members who were trained to serve as research helpers. The duties of the DAT included (1) monitoring the compliance of crew members with data acquisition requirements, (2) assisting crew members with carrying out the data acquisition requirements of the project, (3) scheduling the use of the surrogate task data acquisition equipment, and (4) tending the surrogate task data acquisition equipment.

A.2 Subjective Scales

The perceptual dimension, sleepiness, was selected to assess crew members' perceptions of fatigue. Some years ago, we found that the layperson was unable to differentiate among perceptions of sleepiness, alertness and fatigue (Mackie and Miller, 1978). Ratings of these three perceptual dimensions, provided by commercial truck drivers during open highway operations, were all intercorrelated at $r = 0.8$ and greater. From these three possibilities, the sleepiness dimension was selected here because it has been studied the most. Various sleepiness scales (Stanford, Epworth, Karolinska, etc.) have been used extensively in field and laboratory studies during the last two decades.

Multiple subjective estimates of sleepiness were acquired in the Daily Log with the Stanford Sleepiness Scale (SSS) (Hoddes, Zarcone, Smythe, Phillips, & Dement, 1973). The SSS is shown in Appendix C. Crew members chose one of seven sets of statements describing their state of sleepiness. The strengths of the SSS were that it could be administered many times per day, that it had usually correlated with standard measures of performance and that it had usually reflected the effects of sleep loss. The weaknesses of the SSS were that the extreme values on the scale (1and 7) were known to be used infrequently and that the rank-ordered statements related to more than one perceptual dimension, including sleepiness, alertness and concentration (Horne, 1991).

The Epworth Sleepiness Scale (ESS) was devised at Epworth Hospital in Melbourne Australia (Johns, 1991;1992). The ESS had correlated well with electroencephalographically (EEG) determined sleep latencies measured at night or during the day and was considered to be a validated and reliable self-report measure of sleepiness (Johns, 1991;1992). The crew members used a number from 0 to 3 corresponding to the likelihood (never, slight, moderate, and high, respectively) that they would fall asleep in eight situations such as sitting and reading, watching TV, as a passenger in a car for an hour, etc. The ESS is shown in Appendix C. It was also used in the Background Questionnaire.

The Scripps Visual Analog Sleepiness Scale (SVASS) was based upon the SSS. To deal with the weaknesses of the SSS while trying to retain its strengths, the SSS was adapted to a bipolar, 100-point visual analog scale. The scale was anchored at both ends and the middle with wakefulness-sleepiness descriptors from the SSS, as shown in Figure A-1.

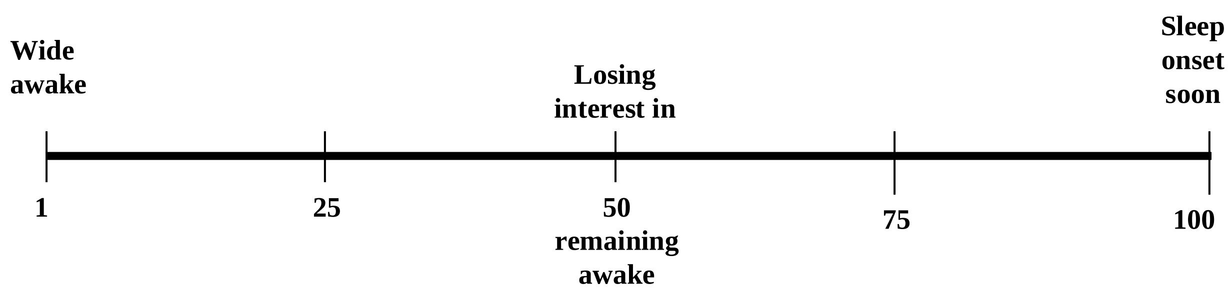

Figure A-1. Scripps Visual Analog Sleepiness Scale.

The crew member used the SVASS by selecting a number from 1 to 100 with reference to the scale. The anchor descriptors on the scale were selected from the SSS (with the midpoint text modified slightly) on the basis of the recommendations by Horne that suggested the creation of parallelism with the alertness-sleepiness descriptors used for the “vigor” factor of the Profile of Mood States (POMS) (Horne, 1991). The POMS vigor scale had also demonstrated sensitivity and reliability with respect to quantifying perceptions of sleepiness.

The SVASS was an executable program for the PC, written by one of the authors (JCM) while at The Scripps Research Institute. It created a data file in ASCII text format with a computer clock date-time stamp and an SVASS rating for each record.

The 15-point physical workload scale used in the Daily Log was one variant of a scale designed to allow estimates of heart rate caused by varying levels of dynamic work (Borg, 1985; Kilbom, 1991). The scale was anchored with a statement at each of the numbers 1, 2.5, 4, 6, 8, 10, 12, 14, and 15. Crew members chose one of the fifteen numbers describing their average physical workload during the preceding work or watch period. The physical workload scale is shown in Appendix C.

The 7-point mental workload scale used in the Daily Log was created by the Crew Performance Branch of the USAF School of Aerospace Medicine in the late 1970s, and then re-examined, linearized, and verified by the Human Factors Branch of the Air Force Flight Test Center (Ames & George, 1993). Crew members chose one of seven sets of statements describing their average mental workload during the preceding work or watch period. The mental workload scale is shown in Appendix C.

The 7-point motion discomfort index (MDI) used in the Daily Log was a simplified, unidimensional scale intended to reflect a monotonic function of motion sickness severity. One of the authors (MEM) is nauseatingly familiar with more complex measures of motion sickness symptomatology (Wiker, Kennedy, McCauley, and Pepper, 1979). But for the purposes of this study, detailed symptom clusters and weighting by major and minor symptoms was considered overly complex and inefficient. The simple scale was anchored with statements at numbers 1 and 7. Crew members chose one of the seven numbers describing their average MDI during the preceding work, watch or major sleep period. The MDI is shown in Appendix C.

A.3 Ergogram

In sleep medicine and research, we use a display called a hypnogram. It is a stepped, horizontal line that shows sleep stage as function of time of night. Similarly, the Federal Highway Administration requires truck drivers to fill in a blank graph in their log books with a stepped, horizontal line that shows duty status (on duty, driving; on duty, not driving; and off duty) as a function of time of day.

The Ergogram is of a form similar to the hypnogram and the trucker's log. It shows three levels of activity: awake, at work or watch; awake, not at work or watch; and in bed. These are plotted as bottom, middle and top of the y axis, respectively, as a function of time of day across ten days. This picture allows the observer to quickly identify periods of regular and irregular work-rest cycles. In addition, the SSS ratings entered in the Daily Log are co-plotted, as well. This combination of data allows the observer to identify matches and mismatches between perceived sleepiness and lengths of time spent awake and in bed.

A.4 Wrist Activity Monitor

The Wrist Activity Monitor (WAM)[9] was a wrist-worn device that contained a single-axis piezoelectric accelerometer sensitive to movements of the arm. Crew members wore the WAM for about 72 hours in order to record periods of wakefulness (activity) and sleep (absence of activity). It was determined during data analysis that 72 hours of data were insufficient to provide

[9] Precision Control Design, Inc., Ft Walton Beach FL

meaningful assessments of crew work-rest schedules. Thus, the WAM data will not be presented in this report.

A.5 Cumulative Sleep Debt

From the Daily Log, we calculated the amount of time spent in bed each calendar day, running from noon to noon. The breakpoint at noon was selected because (1) most on-board sleep is nocturnal or peri-nocturnal, with nearly no sleep episodes ongoing at noon, and (2) the 24-hour sleep value reported at noon affects the status of the individual at Quarters each day, at midday, when he or she is observed regularly by senior personnel.

Cumulative sleep debt was the cumulative total of negative differences between the ideal sleep length and the time spent in bed for each 24-hour period. Thus, each day that a crew member acquired less time in bed than his or her self-reported ideal amount of sleep, the deficit was added to his or her cumulative sleep debt. Cumulative sleep debt, calculated in this manner, reflected the time available to sleep, a workload metric.

A.6 Recovery Sleep

Recovery sleep was the daily (noon to noon) time in bed for those days on which time in bed exceeded the ideal sleep length. Thus, each day that a crew member acquired more time in bed than his or her self-reported ideal amount of sleep, that total time in bed was his or her amount of recovery sleep for that day. During these patrols, recovery sleep days occurred less frequently than days on which sleep debt was accumulated. A cumulative total for recovery sleep was not calculated because it appears that humans cannot "store up" sleep.[10] The occurrence of one or more periods of recovery sleep is a usual consequence of preceding sleep deficit.

Recovery sleep acts to reduce or remove a cumulative sleep debt. We combined the sleep debt pattern with recovery sleep to produce plots that showed cumulative fatigue as reflected in the amount of sleep acquired. These plots showed cumulative sleep debt corrected for recovery sleep, and thus suggested the degree of cumulative fatigue attributable to sleep disruption, especially in terms of sleep deprivation.

A.7 Metabolic Energy Expenditure

The task descriptions were approximated as work in watts (w) by reference to Table A-4, and expressed as energy expenditure (power) in watt-hours once the time that must be spent in each physical activity was recorded.

[10] A fact summarized in a scholarly and readable fashion by Coren, 1996

TABLE A-1
Energy expended by males and females while performing typical activities (Miller & Horvath, 1981). Abbreviation: w, watts.

Activity	Males	Females
Sleeping	77 w	63 w
Sitting	98 w	77 w
Standing	119 w	98 w
Office Work	126 w	112 w
Walking, level	182 w	154 w
Walking, carrying 10 kg	280 w	238 w
Labor; Climbing a staircase	420 w	353 w

The following questions were asked in the Background Questionnaire for both watch (if applicable) and work periods:

- "Your work is/will be (1) almost all sedentary, (2) part sedentary and part standing or walking, (3) almost all standing or walking.
- "If your work is NOT almost all sedentary,
    - "How far do you walk in an *average hour*? You may want to use the Frame numbers of the ship to help with your estimate. ___ feet
    - "How many stairways do you climb? ___ (no.)
    - "Do you lift or carry items when you walk or stand? (1) yes, (2) no
    - "If you DO lift or carry items, *on the average*:
        - "How many times lifted per hour? ___times
        - "How heavy? ___ lb
        - "How far carried? ___ feet"

A.8 General Motivation

Two questions were asked on the Background Questionnaire and two on the Supplemental Questionnaire. The first two questions dealt with the crew member's general, trait-like view of the relationship between the country and the Coast Guard and between the Coast Guard and the crew member. These questions were:

- For our country, the mission of the Coast Guard is...
- For the Coast Guard, your contribution to the mission is...

The second two questions dealt with the crew member's state-like view of the relationship between the country and the Coast Guard and between the Coast Guard and the crew member. These two questions were answered after the midpoint of the data collection period. These questions were:

- For our country, this patrol has been...
- Your contribution to this patrol has been...

The questions were each answered using the following scale, constructed from validated scaling information (Babbitt & Nystrom, 1989):

1. Very important
2. Important
3. Borderline
4. Not important
5. Very unimportant

A.9 Incident Analysis

- Problems arising from fatigue induced by limited-duration, high-demand scenarios, cited by ships' officers, included the following:
    - Mental lapses such as:
        - Mistakes in handling the ship while maneuvering within a fishing fleet, with a potential for collision;
        - Line handling errors during boat launch and recovery that could injure or kill a member of the crew; and
        - Misjudging wind and waves while bringing a boat alongside, with a potential to injure or kill a member of the crew.
    - Physical slips such as trips and falls.

We planned to use *post hoc* interviews to gather descriptive data for these kinds of incidents. Once the incidents were documented, they were grouped and quantified to the degree possible.

A.10 Code Substitution Task

The philosophy for using this task in a maritime setting was described well by Sanquist and his associates (Sandquist, Raby, Maloney, & Carvalhais, 1996). They noted that the task was "appropriate for a broad range of personnel, unlike more complex cognitive tasks..." The code substitution task assesses both associative memory and perceptual speed. It requires competence in visual search mechanisms, encoding of data, decoding of data and rote recall (Kennedy, Dunlap, Turnage, & Fowlkes, 1993). Code substitution performance was assessed using the version of the task available in the Automated Portable Test System (APTS) (Kennedy, Wilkes, Baltzley, & Fowlkes, 1990). The task ran for 90 seconds per trial, and there was one trial per test session.

The data recorded by the task included the number of correct responses and the mean reaction time. The measure used for analysis was "throughput," calculated as the quotient of the number of correct responses and the length of the trial (90 sec). The individual signatures of response speed and response accuracy are combined within this metric. This makes throughput a useful, summary metric for a large-scale project such as this. However, additional analyses would be needed to discriminate variance in speed from variance in accuracy in this application of the Code Substitution task.

A.11 Pattern Matching Task

The human cognitive functions of interest here were those that have been characterized as knowledge-based, as opposed to those functions that are skill-based or rule-based. Knowledge-based functions include the recognition of, and creation of responses to, novel and unpredicted situations for which clearly applicable rules do not exist. This cognitive function is, perhaps, the greatest strength that a human operator can add to a system. Among the actions allocated to the human operator in a system, perhaps the most critical is the combination of failure detection and fault diagnosis.   The crew member is, in many cases, forced to diagnose system failures under the pressure of time stress. Instead of forming hypotheses in a relatively leisurely manner, the crew members probably use a pattern-matching approach to failure diagnosis.

Pattern matching required competence in visual pattern recognition and spatial memory. It was assessed using the successive pattern comparison task in the APTS (Kennedy et al., 1990). The task ran for 90 seconds per trial, and there was one trial per test session. The screen displayed a random pattern of asterisks for 1.5 seconds, then the screen was clear for 3 seconds. The screen then displayed a second pattern of asterisks, for 5 seconds, that was the same pattern or a different pattern. The crew member decided if the pattern was the same as or different from the first and pressed the [S] or [D] key on the system keyboard.

The data recorded from the task included the number of correct responses and the mean reaction time. The measure used for analysis was, again, "throughput," calculated as the quotient of the number of correct responses and the length of the trial (90 sec).

A.12 Vigilance Task

The philosophy for using this task in a maritime setting was described well by Sanquist et al. (1996, Appendix 3). They noted that "(1) the task is similar to that of many jobs involving watchstanding, (2) measures can be taken that directly reflect decision criteria and sensitivity, and (3) the task shows the largest statistical effects [compared to cognitive and memory tasks]." The task is easily learned and quite sensitive to sleep disruption and fatigue.

Vigilance performance was assessed using the Psychomotor Vigilance Task (PVT) (Dinges, 1992). The 8" x 4.5" x 2.4" portable, battery-operated device ran a continuous simple reaction time test for ten minutes. It required sustained attention and motor responses to all stimuli, and was designed to be sensitive to fatigue due to sleep loss. The crew member's job was to watch a digital counter on the device and, when the counter started to run, to turn off the counter as quickly as possible. A relatively quick response was about 200 millisec Due to the shape of the device, crew members referred to it as the "brick.".

Data collected by the PVT included the reaction time for each stimulus presented and each false alarm (any button press that occurred when the counter was not running). The data were reduced by custom software to the number of stimuli presented, mean of the reciprocals of all reaction times, the mean of the reciprocal of the slowest 10% of reaction times, the number of false alarms, and the number of lapses (reaction times slower than 500 millisec) (Dinges et al., 1997). The mean of the reciprocal of the slowest 10% of reaction times and the number of lapses were analyzed.

A.13 Simultaneity Task

This visual function, which differs from the usual static visual acuity test, may be fundamental to the performance of jobs that require complex visual-motor activities (Kennedy, Ritter, Berbaum, & Smith, 1993; Jones & Kennedy, 1995). The visual temporal acuity task measured the briefest mean interval the crew member could perceive between the appearances of two small square symbols on the computer screen. The locations of the squares were unchanging, occurring on either side of a central fixation point. The interval between the appearance of the squares was shortened until errors were made by the crew member, and then lengthened again. This cycle was repeated several times. One trial lasted about a minute, and there was one trial per test session. The number of cycles and the mean and standard deviation of the shortest intervals perceived were recorded, and the mean and standard deviation were analyzed.

A.14 Tapping Speed Task

Historically, this measure has been used to check the fundamental motor speed of crew members. We used the tapping task from the APTS (Kennedy et al., 1990). The crew member attempted to alternately tap two specified, unchanging keys on the computer keyboard as rapidly as possible with the non-preferred hand. The task was performed for three 20-sec trials per test session. The number of successful alternations was recorded for each of the three trials. The number from the second of the three trials was used for analysis.

A.15 Testing Strategy

The testing system and the PVT device were located together at one (WTGB) or two (WHEC, WMEC) testing stations on each cutter. At a testing station, the potential for crew member queuing was mitigated to some degree by parallel testing: while one person used the laptop testing system, another used the PVT device. The FIT was located at one testing station and used with about half the crew members. The crew members were asked to test at least twice per day.

A surge suppresser, an uninterruptable power supply and the system's battery provided three levels of surge protection and two levels of brown-out protection for the computer. A custom looping program appeared upon system boot up. This program served three purposes: (1) it acquired and recorded in a hidden file all 4-digit codes used for system entry, with date and time; (2) coupled with BIOS-level password protection, it prevented access to DOS-level functions by all but research team personnel; and (3) it launched the data acquisition programs. The FIT device, described below, was controlled by the laptop testing system. The PVT vigilance tester was a battery-operated, hand-held, stand-alone device.

The testing station located in the Engineer's Log Room on a WMEC.

The testing station located in the electronics (ET) shop on a WHEC.

The testing station located in the gyroscope room (IC Gyro) on a WHEC.

Each crew member participated in one training session. During that session, they executed successfully one trial each of code substitution and pattern recognition, one trial of simultaneity, and three trials of tapping, and they completed one 1-min demonstration of the vigilance task. Subsequently, the first three trials for each crew member were discarded for each performance test. This removed the sharpest portion of the learning curve for each task.

A.16 Oculometry

The FIT 2000, designed as an industrial fitness-for-duty evaluation system that would detect physiological impairments due to fatigue and many other factors, was used here only as an oculomotor tester. It tested involuntary responses, minimal training was required and there were no learning or skill effects expected. Testing took about 30 seconds.

Baseline pupil size varies as a function of fatigue and or sleepiness (Pressman, DiPhillipo, & Fry, 1986; Schmidt, Jackson, & Knopp, 1981; Yoss, 1969; Ranzijn & Lack, 1997). Saccade velocity slowing may (Moore-Ede, Mitchell, Heitmann, Trutschel, Aguirre, & Hajarnavis, 1996; Krichmar et al., 1997) and may not (Morris & Miller, 1996) be a useful index of fatigue. Similarly, increasing pupil response latency, may (Krichmar et al., 1997) and may not (Ranzijn & Lack, 1997) be a useful indicator of fatigue. However, the combining of these three measures, an approach used with the FIT, has allowed reliable detections of fatigue (personal communications, J. Krichmar and R. Perry, PMI, Inc.). We expected to find cumulative fatigue effects expressed as gradual reductions in baseline pupil size and saccade velocity.

A.17 Procedures

A.17.1 Training

Each subject participated in one training session with either Dr. Miller or Matthew Smith at their assigned testing station. During this training session the subject's personal identification code was initiated on the computer systems and specific training was given on each task.in the PATSYS computer based performance battery. Second, they were shown the use of the PVT, and given a one-minute sample test. On the ships where FIT data were collected, the subjects received training at the FIT testing station. One goal of the training session was that the subjects become capable of starting and performing all the required tests without supervision.

A.17.2 Testing

Number of tests per day: Our goal was to maximize the number of subjects' tests per day without interfering with their work and rest schedules. Since the schedules of crew members varied greatly within and across subjects, there was not a set time at which the subjects were asked to test. Rather, we tried to work out the best possible testing schedule on an individual basis, taking into consideration each particular subject's work/watch schedule. Subjects were asked to test three or four times per day, preferably not at the exact same time every day (to achieve a wider time of day variance with which to gauge circadian rhythm effects). This variability proved to be a natural consequence for most watch standers because their watch times rotated daily. The subjects were encouraged to test before and after watches, and at least one other time during the day – again, each subject according to their schedule.

Ideal test schedules (encouraged test schedules)

- Non-watch stander – before work, after work and one or two more times in the evening

- 1 in 3 watch – non-rotating schedule, with 2 watches and 1 work period any given week-day. Test before morning watch or work, after watch, after work or before 2nd watch and after 2nd watch. Weekends- before and after each watch period

- 1 in 4 / 1 in 5 watch – rotating watch schedule- before and after watches and work periods where possible.

- 1 in 6 watch – non- rotating schedule with 1 watch and 1 work period any given week-day. Before after watch, before or after work, and one other time during the day.

- 1 in 7 or higher – before and after work and watch and another time during the day

Order of testing

The subjects were free to chose the order of testing, being either the PVT or the computer-based PATSYS tests. The FIT testing always came after the PATSYS tests. This flexibility was given in an attempt to alleviate queuing at the testing stations.

A.18 Cumulative Fatigue (Linear) and Circadian Rhythm (Cosinor) Component Extraction

This data reduction process used a custom spreadsheet template which, in turn, was created using methods published in the research literature (Naitoh, Englund, & Rynman, 1985; Koukkari, Duke, Halberg, & Lee, 1974). It apportioned total variance into variance (1) attributable to linear trend (cumulative fatigue), (2) attributable to a cosine function (circadian effect) and (3) attributable to other factors, including random error and acute fatigue. In algebraic form, total variance was apportioned as:

$$s_{\text{total}}^2 = s_{\text{linear}}^2 + s_{\text{cosine}}^2 + s_{\text{other}}^2$$

where s^2 = variance.

The total variance of the multi-day set of observations of performance and subjective ratings for each crew member was calculated. The rectilinear component of a data set was calculated by the least squares method. The intercept on the first day of testing, the slope and the Pearson product moment correlation coefficient were calculated for the regression line. The variance attributable to the linear component was calculated as the difference between the original total variance and the total variance of the residual data values after the linear trend was subtracted from the data, expressed as a percentage of the original total variance. The residual values were subjected to cosinor analysis.

For the cosine curve fit, the spreadsheet reported the mid-point of the waveform (mesor), half-wave amplitude, phase with respect to midnight, the multiple regression coefficient (R), and the F statistic for R. The curve fit assumed a cosine frequency (Ω) of one cycle (360°, 2 π radians) per day and was accomplished by the least-squares method. The variance attributable to the cosine function was calculated as the square of one-half the half-wave amplitude, expressed as a percentage of the original total variance.

The residual variance, remaining after the proportions of variance attributable to rectilinear and cosine regressions had been subtracted, was associated with the effects of acute fatigue and other factors.

A 24-hour cosine curve was fitted to the T_{body} readings by multiple regression. Each fit was characterized by the cosine wave mean (mesor) and by the amplitude and phase angle of the best-fit cosine curve. The amplitude was the half-wave height of the best-fit curve, in degrees F. The phase angle was the time of occurrence of the peak of the best-fit curve (acrophase), which was the estimated mean time at which body temperature peaked during the 24-hour period for an individual.

As with body temperature, a 24-hour cosine curve was fitted to each of the surrogate performance task scores and to all subjective ratings. Again, each fit was characterized primarily by the mean (mesor) and by the amplitude and peak time (acrophase) of the best-fit cosine curve. Each cosine fit was preceded by the removal of linear trend from the data.

A.19 Other Methods

We considered collecting urine specimens and performing biochemical analyses that might reveal stress-induced changes in plasma steroids and catecholamines. It was pointed out to the investigators that urine is acquired on the cutter for forensic purposes. However, the forensic collection system would not support research demands. For one thing, the collection of multiple samples per day per crew member would quickly overload existing storage space. Additionally, a medical corpsman would have to be dedicated nearly full time to the collection, storage and onboard processing of the multiple samples per day for each key crew member. The biochemical kits required for the post-patrol processing of the urine samples were expensive. All of these factors indicated that a large amount of human and financial resources would be required to acquire urinalysis data. Considering that the data would be only moderately reliable, urinalysis was judged not to be cost effective for this project.

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Appendix B

HUMAN PERFORMANCE AND SAFETY IN COAST GUARD OPERATIONS
Contract No. DTCG39-94-D-E00777
INFORMED CONSENT TO SERVE AS A RESEARCH SUBJECT

The research project was explained to me by____________________________________on _______________(date).

- I understand that this research project will try to determine whether present operations aboard USCG cutters may contribute to excessive crew fatigue and thereby expose crew members to unnecessarily high risks of incidents, accidents, injury, and mission failure, and that this research project addresses that concern by measuring my workload, strain, fatigue, and performance.
- I understand that I will provide information about my level of sleepiness, my level of seasickness, the demands of my job and my work-rest schedule; and that my performance of my duties will be measured, that my performance of several computerized tasks will be measured, that my wrist activity will be measured, and that my eye movements will be measured.
- I understand that I will receive no direct benefits, such as extra pay or leave, for my participation, but that, by my participation, I will be contributing indirectly to general knowledge about how to conduct safe operations on Coast Guard cutters.
- I understand that there are no added risks of physical injury associated with my participation, beyond those that exist in my performance of my Coast Guard duties.
- I understand that my name will not be associated with data collected from me for this project in any publication without my written permission, and that the Privacy Act of 1974 applies to my data.
- I understand that I may withdraw my participation from the project at any time without any negative action being taken against me by the researchers or by the Coast Guard.
- I understand that, for further information about the project, I may contact Anita Rothblum, Ph.D., C.P.E., U.S. Coast Guard Research and Development Center, Systems Analysis Branch, 1082 Shenecossett Road, Groton, Connecticut 06340-6096, or James C. Miller, Ph.D., C.P.E., Monterey Technologies, Inc., 987 University Ave., Suite 12, Los Gatos, California 95030.
- I agree to serve as a research subject for this project.

Subject: _____________________ _____________________
Print Sign

Researcher: _____________________ _____________________
Print Sign

Witness: _____________________ _____________________
Print Sign

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APPENDIX C
CREW MEMBER’S DAILY LOG

Each member of the crew participating in this study was issued a log book. Each log book is approximately 5 inches tall and 3--1/4 inches wide and was sufficient for a period of 10 days.

Identification information was put on the outside front cover of the log book The inside of the front cover provided contact information regarding this study. The first few pages contained brief instructions.

Prior to beginning each weekly log book, the crew member was asked to complete the pages on RISK OF FALLING ASLEEP and WATCH FATIGUE. The daily log pages followed. With the exception of the cover sheet indicating the day, all the daily log sheets were identical. For that reason, only the log sheets for days 1 and 2 are reproduced here; days 3 - 10 are omitted for brevity.

USCG

CREW MEMBER'S

DAILY LOG

1996

Name: ___________________________

Cutter: ___________________________

Department: ______________________

Division: _________________________

This Log Start Date: _______________

MONTEREY
TECHNOLOGIES, INC.

For information about this Log, please call James C. Miller, Ph.D., 619-443-4427, or Paula Sind-Prunier, Ph.D., USCG R&DC, 860-441-2891.

Prepared by
Monterey Technologies, Inc.
Los Gatos, California
No copyright

1

Thank you for participating in this USCG R&D study and for agreeing to use this Crew Member's Daily Log. The Log provides a record of your daily pattern of work, rest and sleep and your responses to that pattern. Your data will be used to help make decisions about staffing on USCG cutters. Your data will not be associated with your name in any report.

INSTRUCTIONS

The first page in this Log is called the **Risk of Falling Asleep Page**. Read the instructions on that page and fill it in on the day you start this log.

The second page of the log is called the **Watch Fatigue Page**. Fill it in on the day you start this log.

The rest of this Log is divided into 10 sections. Each **section** represents **one day**. Each section has the same set of pages:

- 3 work pages
- 3 sleep/nap pages
- Temperature record page

Please **start** with the first section, labeled Day 1 on the day you start this Log. Start a

2

new section each day at **midnight** (0000 hrs) and end a section at 2359 hrs. Always use the 24-hor clock to write times. If you **miss** some data, and cannot remember it at all, write "MISSED" in that area. Keep missed data to a minimum: what you **remember** is better than no data at all.

You may not need every page in a section every day. Also, there are some **extra** pages at the end of the Log that may be used on days when 3 pages are not enough. Please write dates on these extra pages.

The following paragraphs contain specific instructions for each kind of page.

WORK PAGE

(a) Check one of the top two choices, " watch period" **or** "work day." (b) Write in the time watch or work **starts** and your Sleepiness Rating (below) at the time watch or work starts. (c) Write in the average physical and mental workload ratings and maximum motion discomfort (below) you experience **during** the period. (d) Write in the time work **ends** and your Sleepiness

3

Rating at the time the period ends. If you have a break of more than **one hour**, or you change from watch to work or work to watch, start a new Work Page. Start the first day at midnight. If you stand watch or work past midnight, show it ending on a Work page in the next day's section of the Log. End the last day at midnight, then get a new book.

SLEEP/NAP PAGE

(a) Write in the time you get **into bed** and your Sleepiness Rating (below) at that time. (b) Write in the number of **minutes** you think it took you to **fall asleep**. (c) Write in the time you get **out of bed** and your Sleepiness Rating at that time. (d) Write in the maximum motion discomfort (below) you experienced while in bed. If you are out of bed more than **one hour**, start a new Sleep/Nap Page. Start the first day at midnight. If you sleep past midnight, show it ending on a Sleep/Nap Page in the next day's section of the Log. End the last day at midnight, then get a new book.

4

SLEEPINESS SCALE

When you are asked on a Sleep/Nap Page or a Work Page to "Rate your sleepiness (1-7)," fill in the number that is your best estimate of your feeling of sleepiness for the time specified using this scale:

1. Feeling active and vital; alert; wide awake.
2. Functioning at a high level, but not at peak; able to concentrate.
3. Relaxed; awake; not at full alertness; responsive.
4. A little foggy; not at peak; let down.
5. Fogginess; beginning to lose interest in remaining awake; slowed down.
6. Sleepiness; prefer to be lying down; fighting sleep; woozy.
7. Almost in reverie; sleep onset soon; lost struggle to remain awake.

5

MENTAL WORKLOAD SCALE

When you are asked on a Work Page to "Rate your **average** mental workload (1-7)," fill in the number that is your best estimate of your average mental workload across the whole work period. Use this scale:

1. Nothing to do; no system demands.
2. Light activity; minimum demands
3. Moderate activity; easily managed; considerable spare time.
4. Busy; challenging but manageable; adequate time available.
5. Very busy; demanding to manage; barely time enough.
6. Extremely busy; very difficult; non-essential tasks postponed.
7. Overloaded; system unmanageable; essential tasks undone; unsafe.

6

PHYSICAL WORKLOAD SCALE

When you are asked on a Work Page to "Rate your **average** physical workload (1-15)," fill in the number that is your best estimate across the whole work period. Use this scale:

1. No exertion at all
2.
2.5 Extremely light
3.
4. Very light
5.
6. Light
7.
8. Somewhat hard
9.
10. Hard (heavy)
11.
12. Very hard
13.
14. Extremely hard
15. Maximal exertion

7

MOTION DISCOMFORT SCALE

When you are asked on the to "Rate your **peak** motion discomfort (1-7)," fill in the number that is your best estimate of the maximum you experienced during the period. Use this scale:

1. Normal, symptom free
2.
3.
4.
5.
6.
7. Severe discomfort; unable to work

TEMPERATURES

There is a Temperature Record Page for each day. Use this page to write down the ear temperatures you measure with the Thermoscan device.

8

RISK OF FALLING ASLEEP PAGE

How likely are you to doze off or fall asleep in the following situations, in contrast to just feeling tired? This refers to all of the last week. Even if you have not done these things, estimate their effect on you. Use this scale, and **enter one number on each line:**

1. Would *never* doze
2. *Slight* chance of dozing
3. *Moderate* chance of dozing
4. *High* chance of dozing

a______ Sitting and reading
b______ Watching TV
c______ Sitting inactive in a public place; for example, a theater or meeting
d______ As a passenger in a car for an hour without a break
e______ Lying down to rest in the afternoon when circumstances permit
f_______ Sitting and talking to someone
g______ Sitting quietly after lunch without alcohol
h______ In a car while stopped for a few minutes in traffic

9

WATCH FATIGUE PAGE

For the last week:

During A Watch Period

Your ***typical*** state?

( ) Sleepy ( ) Somewhat sleepy
( ) Somewhat alert
( ) Alert ( ) Very alert

About how often do you feel ***sleepy***?

( ) Never
( ) Less than once a month
( ) Once or twice a month
( ) Once a week
( ) Two or three times a week
( ) About every day

End of A Watch Period

How ***physically tired*** do you usually feel?

( ) Not at all ( ) A little
( ) Quite a bit ( ) Extremely

How ***mentally tired*** do you usually feel?

( ) Not at all ( ) A little
( ) Quite a bit ( ) Extremely

How ***tense*** do you usually feel?

( ) Not at all ( ) A little
( ) Quite a bit ( ) Extremely

START OF LOG
Please leave no blanks

DAY 1 **Date _________** **(0000 - 2359)**	**SLEEP/NAP PAGE** (use the 24-h clock) **Start of Time in Bed** Time: _______ Rate your before-sleep **sleepiness** (1-7): ____ **End of Time in Bed** Time: _______ Rate your after-sleep **sleepiness** (1-7): ____ Rate your **peak motion discomfort** while in bed (1-7): ____ **In Bed** How many minutes did it take you to fall asleep? _____ minutes How long did you sleep? _____ hours _____ minutes

WORK PAGE
(use the 24-h clock)

___ Watch **or** ___ Work Period

Start of Watch or Work
Time: ________
Rate your before-work
sleepiness (1-7): ____

End of Watch or Work
Time: ________
Rate your after-work
sleepiness (1-7): ____

During Watch or Work
Rate your **average mental** workload (1-7): _____
Rate your **average physical** workload (1-15): _____
Rate your **peak motion discomfort** (1-7): _____

WORK PAGE
(use the 24-h clock)

___ Watch **or** ___ Work Period

Start of Watch or Work
Time: ________
Rate your before-work
sleepiness (1-7): ____

End of Watch or Work
Time: ________
Rate your after-work
sleepiness (1-7): ____

During Watch or Work
Rate your **average mental** workload (1-7): _____
Rate your **average physical** workload (1-15): _____
Rate your **peak motion discomfort** (1-7): _____

WORK PAGE
(use the 24-h clock)

___ Watch **or** ___ Work Period

Start of Watch or Work
Time: _______
Rate your before-work
sleepiness (1-7): ____

End of Watch or Work
Time: _______
Rate your after-work
sleepiness (1-7): ____

During Watch or Work
Rate your **average mental** workload (1-7): _____
Rate your **average physical** workload (1-15): _____
Rate your **peak motion discomfort** (1-7): _____

SLEEP/NAP PAGE
(use the 24-h clock)

Start of Time in Bed
Time: _______
Rate your before-sleep
sleepiness (1-7): ____

End of Time in Bed
Time: _______
Rate your after-sleep
sleepiness (1-7): ____
Rate your **peak motion discomfort** while in bed (1-7): ____

In Bed
How many minutes did it take you to fall asleep? _____ minutes

How long did you sleep?

_____ hours _____ minutes

SLEEP/NAP PAGE
(use the 24-h clock)

Start of Time in Bed
Time: _______
Rate your before-sleep
sleepiness (1-7): ____

End of Time in Bed
Time: _______
Rate your after-sleep
sleepiness (1-7): ____
Rate your **peak motion discomfort** while in bed (1-7): ____

In Bed
How many minutes did it
take you to fall asleep? _____ minutes

How long did you sleep?

_____ hours _____ minutes

SLEEP/NAP PAGE
(use the 24-h clock)

Start of Time in Bed
Time: _______
Rate your before-sleep
sleepiness (1-7): ____

End of Time in Bed
Time: _______
Rate your after-sleep
sleepiness (1-7): ____
Rate your **peak motion discomfort** while in bed (1-7): ____

In Bed
How many minutes did it
take you to fall asleep? _____ minutes

How long did you sleep?

_____ hours _____ minutes

TEMPERATURE RECORD PAGE
(use the 24-h clock)

Time: _______ Temperature: _________

Time: _______ Temperature: _________

Time: _______ Temperature: _________

Time: _______ Temperature: _________

Time: _______ Temperature: _________

Time: _______ Temperature: _________

Time: _______ Temperature: _________

Time: _______ Temperature: _________

Time: _______ Temperature: _________

Time: _______ Temperature: _________

Time: _______ Temperature: _________

DAY 2

Date _________
(0000 - 2359)

SLEEP/NAP PAGE
(use the 24-h clock)

Start of Time in Bed
Time: _______
Rate your before-sleep
sleepiness (1-7): ____

End of Time in Bed
Time: _______
Rate your after-sleep
sleepiness (1-7): ____
Rate your **peak motion discomfort** while in bed (1-7): ____

In Bed
How many minutes did it take you to fall asleep? _____ minutes

How long did you sleep?

_____ hours _____ minutes

WORK PAGE
(use the 24-h clock)

___ Watch **or** ___ Work Period

Start of Watch or Work
Time: _______
Rate your before-work
sleepiness (1-7): ____

End of Watch or Work
Time: _______
Rate your after-work
sleepiness (1-7): ____

During Watch or Work
Rate your **average mental** workload (1-7): _____
Rate your **average physical** workload (1-15): _____
Rate your **peak motion discomfort** (1-7): _____

WORK PAGE
(use the 24-h clock)

___ Watch **or** ___ Work Period

Start of Watch or Work
Time: _______
Rate your before-work
sleepiness (1-7): ____

End of Watch or Work
Time: _______
Rate your after-work
sleepiness (1-7): ____

During Watch or Work
Rate your **average mental** workload (1-7): _____
Rate your **average physical** workload (1-15): _____
Rate your **peak motion discomfort** (1-7): _____

WORK PAGE
(use the 24-h clock)

___ Watch **or** ___ Work Period

Start of Watch or Work
Time: _______
Rate your before-work
sleepiness (1-7): ____

End of Watch or Work
Time: _______
Rate your after-work
sleepiness (1-7): ____

During Watch or Work
Rate your **average mental** workload (1-7): _____
Rate your **average physical** workload (1-15): _____
Rate your **peak motion discomfort** (1-7): _____

SLEEP/NAP PAGE
(use the 24-h clock)

Start of Time in Bed
Time: _______
Rate your before-sleep
sleepiness (1-7): ____

End of Time in Bed
Time: _______
Rate your after-sleep
sleepiness (1-7): ____
Rate your **peak motion**
discomfort while in bed (1-7): ____

In Bed
How many minutes did it
take you to fall asleep? _____ minutes

How long did you sleep?

_____ hours _____ minutes

SLEEP/NAP PAGE
(use the 24-h clock)

Start of Time in Bed
Time: _______
Rate your before-sleep
sleepiness (1-7): ____

End of Time in Bed
Time: _______
Rate your after-sleep
sleepiness (1-7): ____
Rate your **peak motion**
discomfort while in bed (1-7): ____

In Bed
How many minutes did it
take you to fall asleep? _____ minutes

How long did you sleep?

_____ hours _____ minutes

SLEEP/NAP PAGE
(use the 24-h clock)

Start of Time in Bed
Time: _______
Rate your before-sleep **sleepiness** (1-7): ____

End of Time in Bed
Time: _______
Rate your after-sleep **sleepiness** (1-7): ____
Rate your **peak motion discomfort** while in bed (1-7): ____

In Bed
How many minutes did it take you to fall asleep? _____ minutes

How long did you sleep?

_____ hours _____ minutes

TEMPERATURE RECORD PAGE
(use the 24-h clock)

Time: _______ Temperature: _________

Time: _______ Temperature: _________

Time: _______ Temperature: _________

Time: _______ Temperature: _________

Time: _______ Temperature: _________

Time: _______ Temperature: _________

Time: _______ Temperature: _________

Time: _______ Temperature: _________

Time: _______ Temperature: _________

Time: _______ Temperature: _________

Time: _______ Temperature: _________